Volume 51 December 1956 Number 8

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PARAGENESIS AND STRUCTURE OF PITCHBLENDE-BEARING VEINS, CENTRAL CITY DISTRICT, GILPIN COUNTY, COLORADO[1]

PAUL K. SIMS

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ABSTRACT

Pitchblende occurs locally along early Tertiary gold-, silver-, and sulfide-bearing quartz veins in the Central City district, Colorado, within the mineral belt of the Front Range. The veins cut a complex mass of Precambrian metamorphic and igneous rocks and early Tertiary intrusive porphyritic rocks.

The veins are fissure fillings that formed at intermediate temperatures and pressures. They consist mainly of pyrite, sphalerite, and galena in a quartz gangue, but also contain tennantite, chalcopyrite, enargite, and pitchblende. The veins differ in quantitative mineralogy, and they can be classified as pyrite-type and galena-sphalerite-type veins.

[1] Publication authorized by the Director, U. S. Geological Survey. Presented before the Society of Economic Geologists, New Orleans meeting, November 1955.

Vein filling took place during three stages of mineralization, from oldest to youngest: a uranium stage, a pyrite stage, and a base-metal stage. Major periods of fracturing and vein reopening took place between the vein-forming stages.

The pyrite and base-metal stages of mineralization were of broad areal extent and produced a concentric zonal arrangement of the ores in the district. In contrast, the uranium stage of mineralization was local in extent and resulted in scattered clusters of uranium deposits, which show no definite spatial relation to the district-wide zoning pattern.

Pitchblende is present in only a few veins. The ore bodies are localized in structurally controlled open spaces along faults. They occur locally along four of the six vein sets of the district, in the form of ore shoots or small lenses and pods that are separated by vein material essentially devoid of uranium. The shoots are small and measure at most a few tens of feet in height and length, and average less than a foot in width; few contain more than 50 tons of ore. Some of the shoots are systematically arranged within the veins but others are erratically distributed.

INTRODUCTION

PITCHBLENDE was first discovered in the United States at the Wood mine in the Central City district in 1871. The Central City district, since the discovery, has been a sporadic producer of uranium ore, and ore containing more than 100,000 pounds of U_3O_8 has been shipped; most of the yield was prior to

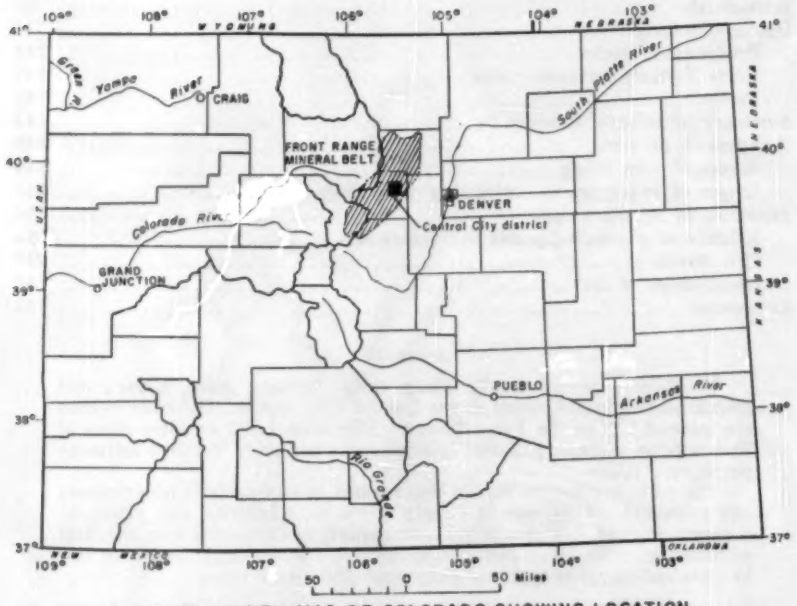


FIGURE 1.—INDEX MAP OF COLORADO SHOWING LOCATION OF CENTRAL CITY DISTRICT.

World War I. Only recently this region was replaced as the country's leading producer of high-grade vein pitchblende ore by the Marysvale, Utah, area.

The Central City district constitutes an area of about 12 square miles in Gilpin County, Colo., about 30 miles west of Denver (Fig. 1). It is the most important of several well-known precious-metal and base-metal mining camps in the mineral belt of the Front Range. Since 1859 when gold was discovered in the area, the district has yielded ores valued at more than $100 million. About 85 percent of the values have been in gold, but substantial amounts have also been recovered from silver, lead, copper, and zinc, as well as uranium. Although the production has come from about 500 mines, a few large mines have supplied a substantial proportion of the ore.

Several papers describing certain aspects of the pitchblende deposits of the Central City district have been published. The most important of these are those by Pearce (15), Rickard (18), Moore and Kithil (14), Alsdorf (1), Bastin (4, 5), Bastin and Hill (6), Lovering and Goddard (13), Phair (16), and Phair and Levine (17). U. S. Geological Survey Professional Paper 94 (Bastin and Hill, 6) has been the principal source of information on the deposits.

During the past several years the U. S. Geological Survey, on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, has been restudying the Central City district and adjoining mining areas, to determine the geology and economic importance of the uranium occurrences in the region. This report presents some of the new data obtained during the investigation that have a bearing on the economics of the deposits and on exploration. It describes briefly the paragenesis of the pitchblende-bearing veins and the structure of the deposits. The other valuable minerals of the veins are discussed only insofar as needed to provide the geologic setting.

During the investigation of the Central City district, from 1952 to 1954, the writer was associated with several members of the U. S. Geological Survey, and their work materially aided in the preparation of this report. The writer wishes particularly to acknowledge the data contributed by A. A. Drake, Jr., E. W. Tooker, and A. E. Dearth.

GEOLOGIC SETTING

The Central City district is in the core of the Front Range of Colorado—a complex of Precambrian metamorphic and igneous rocks, early Tertiary intrusive dikes and irregular plutons, and early Tertiary veins. The Precambrian rocks in the district consist dominantly of a wide variety of felsic gneisses and granites that are folded along northeast-trending axes. The early Tertiary intrusives are porphyritic rocks mainly having the composition of quartz monzonite, bostonite, and quartz bostonite. Faulting, which both preceded and followed the emplacement of the Tertiary intrusives, produced a mesh-like fracture pattern composed of six distinct fracture sets; these fractures were later filled with veins containing precious-metal, base-metal, and uranium minerals that constitute the ore deposits of the district.

Precambrian Rocks.—The Precambrian rocks of the Central City district

consist of an interlayered and generally conformable sequence of metasedimentary and igneous units; some of the latter are metamorphosed. The principal rock types, in order of probable relative age, are given in Table 1.

The metasedimentary units—biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss—and quartz monzonite gneiss are dominant in the district, and they constitute about 75 percent of the bedrock. The other units, although locally abundant, form relatively small, generally lenticular bodies in the metasedimentary biotite gneisses and the quartz monzonite gneiss. The metamorphic rocks belong to Eskola's amphibolite facies (10).

Aside from the biotite-muscovite granite and the post-granite pegmatite, the rocks are metamorphosed and folded. The major fold axes trend northeasterly and plunge gently to the northeast or southwest. The folds are predominantly open and, except locally, the limbs dip less than 60°.

TABLE 1

PRINCIPAL PRECAMBRIAN ROCK UNITS, CENTRAL CITY DISTRICT, IN ORDER OF PROBABLE RELATIVE AGE*

Pegmatite	Some pegmatite is abnormally radioactive.
Biotite-muscovite granite	Equivalent to Silver Plume granite at Silver Plume, Colo.
Quartz diorite and hornblendite	
Granodiorite	Probably equivalent to Boulder Creek granite of Lovering and Goddard (13).
Pegmatite and granite gneiss	Also constitute felsic layers in migmatites. Granite gneiss is sparse in district.
Quartz monzonite gneiss	Granite gneiss of Bastin and Hill (6). Age relative to rocks below is obscure.
Cordierite-cummingtonite gneiss Biotite-quartz-plagioclase gneiss Sillimanitic biotite-quartz gneiss Lime-silicate gneiss Skarn and related rocks Amphibolite Quartzite (or quartz gneiss)	Age relations among rock units are unknown. Most of the rocks previously were grouped in the Idaho Springs formation of Ball (3).

* Rocks are listed from youngest to oldest.

Early Tertiary Intrusive Rocks.—The porphyritic igneous rocks that cut the Precambrian rocks of the Central City district are dominantly quartz monzonite porphyry and bostonites, but also include granodiorite porphyry. The quartz monzonite and granodiorite form small irregular plutons and dikes, and in the southeast part of the district they constitute a substantial proportion of the bedrock. The bostonite-type intrusives can be subdivided into two distinct groups—bostonite and quartz bostonite. The bostonite commonly occurs as steep-walled, narrow dikes that trend easterly. The quartz bostonites similarly form narrow dikes, but they are more varied in orientation; most trend northwest but a few trend northeast or in other directions. The bostonite and quartz bostonite dikes are a foot or less to about 50 feet wide, and some are more than 2 miles long. The pattern of the quartz bostonite dikes within a part of the district, the Eureka Gulch area, can be seen in the report by Sims, Osterwald, and Tooker (19, pl. 1). The regional pattern is shown by Bastin and Hill (6).

Recent studies by Phair (16) of the early Tertiary intrusive sequence have disclosed that it is one of the most radioactive igneous series in the world. All the porphyries are more radioactive than "the average granitic rock," and the quartz bostonite is 10 to 20 times more radioactive than "the average granitic rock."

Faults.—A complex fracture system was formed during the Laramide orogeny as the result of two separate periods of faulting. Early Laramide faults formed before the emplacement of the porphyries; later Laramide faults developed after the intrusion of most of the porphyry sequence. Both periods of faulting preceded the mineralization, but recurrent movements took place during mineralization.

During the earlier period of faulting, persistent, steeply dipping, northwestward-trending fractures were formed. These are members of Lovering's "breccia reef" system. Only two faults of this system—the Blackhawk and the J. L. Emerson—are present in the Central City district. The Blackhawk fault is barren; the J. L. Emerson fault—the northwest extension of the great Gem Lode in the Idaho Springs district (6, p. 290–292)—has been a minor source of ore. The faults are left-hand faults, the northeast side having moved northwest relative to the southwest side. The apparent horizontal displacement commonly is several tens of feet to several hundred feet; the vertical component is substantial but less than the horizontal displacement.

During the later period of faulting, a complex mesh-like fracture pattern was developed. The faults generally dip at an angle steeper than 60°, and they are less continuous than the older faults. Five principal fault sets, distinguished by their trend, are recognized; and, although they appear to have formed essentially contemporaneously from the same regional (?) shear, they generally developed in the following sequence, from oldest to youngest; west-northwest trending, east trending, east-northeast trending, northeast trending, and north-northeast trending. The displacement along individual faults of all sets is small, and to judge from the offset of steeply dipping porphyry dikes the component of movement is largely horizontal. The apparent horizontal displacement rarely exceeds 10 feet. The faults of this system originated before mineralization, but movements that formed openings along the fractures took place during the filling.

SUMMARY OF MINERAL DEPOSITS

The mineral deposits of the Central City district are gold-, silver-, copper-, lead-, zinc-, and uranium-bearing veins of early Tertiary age that were formed as fissure fillings in the faults. Most of the values are in gold. Uranium, a local constituent of the ores, occurs in the same veins as the sulfides.

The veins are similar in mineralogy and structure to the deposits classified by Lindgren (12, p. 530–532) as mesothermal. They range from single, well-defined fissure fillings to complex, branching lodes. Although few veins are more than a thousand feet long, some are a mile or more in length, and one vein system—the California-Gardner-Mammoth—is at least 12,000 feet long. The California vein has been mined to a depth of 2,200 feet, the deepest pene-

tration in the district. The veins average 1 to 3 feet in width, but locally they are 5 to 10 feet or more wide.

A narrow zone of altered wall rock surrounds the veins (E. W. Tooker, oral communication). A few inches of hard, bleached wall rock adjacent to the vein is partly altered to sericite and locally to silica. This zone of hard, altered rock is bordered by a few inches of soft, white rock composed of montmorillonite, illite, and kaolinite that grades outward into fresh rock. Pyrite is disseminated in the hard, bleached rock adjacent to the vein and at places also occurs in the softer clay zone.

The principal metallic minerals are the sulfides and sulfosalts of iron, copper, lead, and zinc; uranium oxide, silver-bearing sulfosalts, gold tellurides, and free gold occur locally. Quartz is the dominant gangue mineral, but the carbonates ankerite, rhodochrosite, siderite, and calcite are locally present in a few veins and fluorite occurs at places in the southeast part of the district.

The veins differ in quantitative mineralogy; they can be divided into two main types, veins of pyrite type and veins of galena-sphalerite type. Although the two types are distinctive, they grade into one another through gradual changes in the proportions of the constituent minerals; some veins change along strike from one mineralogic type into the other.

The veins of the pyrite type consist mainly of pyrite and quartz, with subordinate, but locally abundant, chalcopyrite, tennantite, enargite, sphalerite, and galena, and sparse pitchblende. The base-metal sulfides and sulfosalts, where present in the veins, occur as two distinctive mineral assemblages, one consisting dominantly of copper minerals and the other consisting of intergrown sphalerite, galena, and copper minerals. The former can be worked for copper at places, and the latter can be mined for lead and zinc as well as copper. Because of these distinctive mineralogic differences, the pyrite veins can be subdivided into three subtypes. These are: subtype A—pyrite veins that consist almost wholly of pyrite and gangue, subtype B—pyrite veins that contain copper sulfides and sulfosalts as the dominant base-metal minerals, and subtype C—pyrite veins that contain roughly equal quantities of sphalerite, galena, and copper minerals.

The veins of the galena-sphalerite type contain dominant sphalerite and galena. Pyrite is ubiquitous in these veins, but it is never abundant; copper minerals are minor constituents and pitchblende and silver sulfosalts are rare. Carbonates locally are the dominant gangue and barite is rarely present.

The veins that contain tellurides of gold are confined to the southeast part of the district and appear to be local, unusual variants of the ores, as suggested previously by Bastin and Hill (6, p. 105). Commonly fluorite is an important gangue in these veins.

A concentric zonal arrangement of the ores is clearly shown by the geographic distribution of the pyrite type and galena-sphalerite type veins (Fig. 2). A core area or central zone of pyrite veins, 2 to 3 miles in diameter, is surrounded by an intermediate zone of transitional veins, which in turn is surrounded by a peripheral zone of galena-sphalerite type veins. The central zone contains pyrite veins of subtypes A and B that are chiefly valuable for their gold content. The intermediate zone contains pyrite veins of subtype

C. The pyrite veins of subtype B and C were formed by composite mineralization, as described later under the section on paragenesis. The galena-sphalerite veins of the peripheral zone are mined for base metals as well as gold and silver, but except in the zone of supergene enrichment gold values generally are low. Because the veins of different mineral composition are gradational, the demarcation between zones is necessarily arbitrary. It is probable, but it cannot be conclusively demonstrated, that a depth zoning also is present in the district.

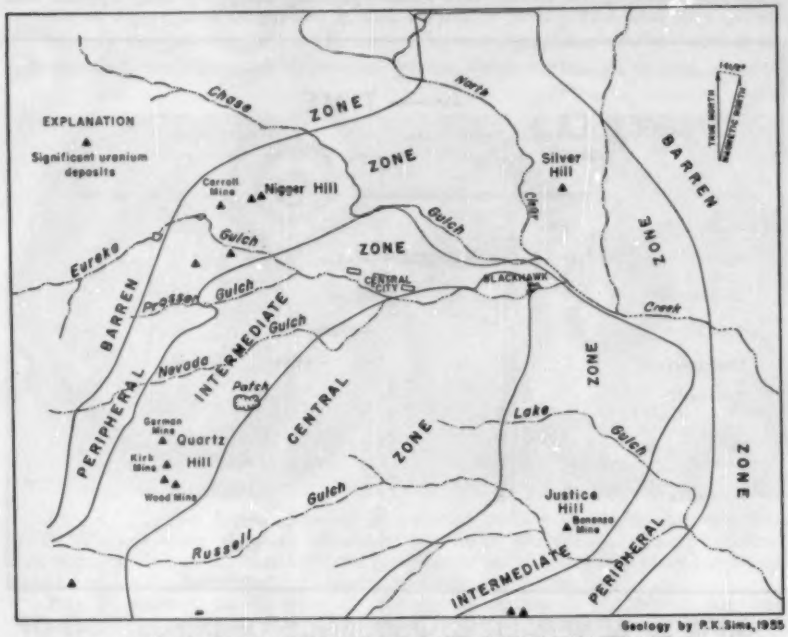


FIGURE 2.-MAP OF CENTRAL CITY DISTRICT SHOWING RELATION OF SIGNIFICANT URANIUM DEPOSITS TO ZONING OF MINERAL DEPOSITS

PARAGENESIS OF VEINS

Although the veins were formed during a single period of mineralization, the vein minerals were deposited during 3 distinct stages, from oldest to youngest: a uranium stage, a pyrite stage, and a base-metal stage. Intense fracturing that locally reopened the fissures separated each of the stages of vein filling, resulting in the local development of composite ores. Probably the recurrent fracturing that separated each of the stages took place essentially contemporaneously throughout the district, but this cannot be proved.

The pyrite and base-metal stages of mineralization resulted in the concen-

tric zonal arrangement of the ores. The uranium stage of mineralization, in contrast, was local and resulted in scattered clusters of uranium deposits that show no direct correlation with the zoning pattern. It is presumed that the pyrite and base-metal mineralization stemmed from a single source, probably deep seated, beneath the core of the district; and that the uranium stage mineralization came from several relatively shallow, separate sources.

Stages of Vein Filling.—A distinctive suite of minerals was deposited during each of the three stages of mineralization. During the uranium stage, pitchblende and sparse pyrite were formed; during the pyrite stage, pyrite was

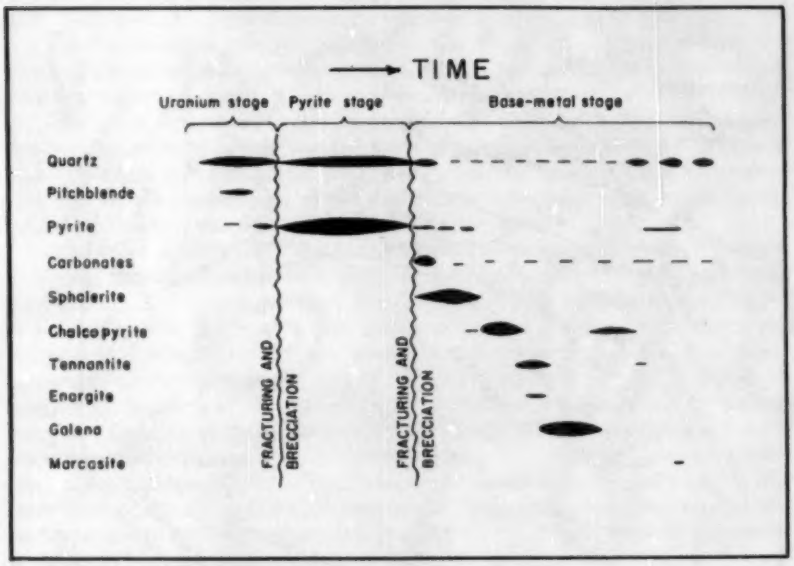


FIGURE 3.-GENERALIZED SEQUENCE OF DEPOSITION OF PRINCIPAL VEIN-FORMING MINERALS, CENTRAL CITY DISTRICT

the only metallic mineral formed; and during the base-metal stage, galena, sphalerite, copper minerals, and rarely, pyrite and sulfosalts were deposited. Most of the gold and silver was introduced during the base-metal stage of mineralization. Quartz accompanied all stages of mineralization; the carbonate minerals were deposited only during the base-metal stage.

The generalized sequence of deposition of the principal vein-forming minerals, within faults of all fracture sets, is given in Figure 3. The vein minerals, for which few data are available, are not shown in the diagram. Also not shown are the minor periods of fracturing which are important locally in some veins but which do not appear to be regional in scope.

During the uranium stage, quartz, pitchblende, and pyrite were deposited. The quartz is gray to white and crystalline, and at most places it was the first mineral to crystallize. Pitchblende began to form somewhat after the beginning of quartz deposition, developing wholly by filling. Most of the pyrite crystallized later than the pitchblende, and in large part it veins both the pitchblende and the quartz; some of it, however, crystallized contemporaneously with the pitchblende. In some veins pyrite was not deposited during this stage. The pitchblende characteristically developed spheroidal forms; a typical specimen is shown in Figure 4. In addition to forming spheroidal grains or aggregates of grains, it also occurs in vein forms and tiny pellets, and rarely irregular, dendritic forms. The outer surfaces of the veinlets are subrounded, and, like the spheroidal grains, have shrinkage cracks, particu-

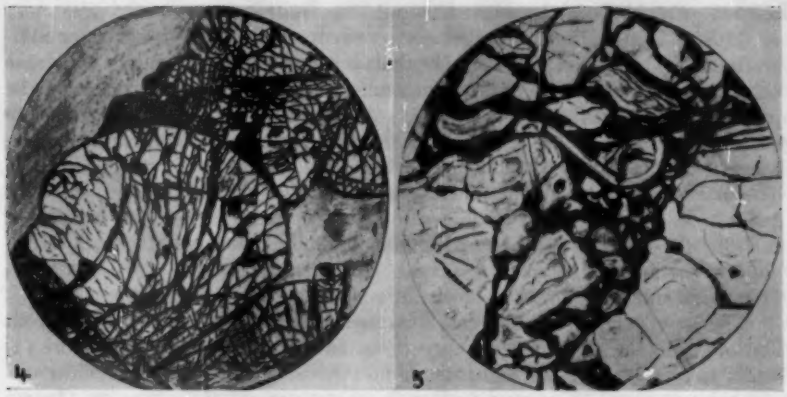


FIG. 4. Camera lucida drawing of polished surface of pitchblende ore from J. P. Whitney mine, showing spheroidal outline of pitchblende. The pitchblende has radial shrinkage cracks; both the pitchblende and the quartz (black) are fractured and locally brecciated. Diameter of circle is 3.3 mm.

FIG. 5. Camera lucida drawing of polished surface of pitchblende ore from Wood vein, 583-foot level west, East Calhoun mine, showing brecciated pitchblende in a quartz (black) matrix. Diameter of circle is 3.3 mm.

larly radial cracks. The pitchblende generally is fractured and broken; at places, as shown in Figure 5, the fragments are finely comminuted and partly rotated. In the Wood vein on Quartz Hill (9), minor fracturing took place during pitchblende formation, and as a result, brecciated fragments of pitchblende locally are cemented by later pitchblende and quartz.

A major period of fracturing preceded the pyrite stage of mineralization. It resulted in the brecciation of pitchblende and its associated minerals, as described above, and in the development of conspicuous, widespread, new openings along the faults. During the pyrite stage of mineralization, pyrite and quartz were deposited. Much of the pyrite that is disseminated through the altered wall rocks of the pyrite veins probably was formed before and during

this stage, but some of it may have formed before the uranium stage of mineralization.

Following another period of recurrent movement, which again reopened the fissures, the minerals of the base-metal stage were deposited. At most places these minerals were deposited in openings that crosscut the earlier pyrite-quartz filling or the pitchblende-bearing seams, but rarely they were deposited as crusts on the older vein minerals. Crystallization during this stage, as determined by the veining of older minerals by younger minerals, followed the commonly observed paragenetic sequence and, in general, began with sphalerite, which was followed by chalcopyrite and copper sulfosalts, galena, chalcopyrite, and pyrite (Fig. 3). In addition to quartz, the carbonates—ankerite, rhodochrosite, siderite, and sparse calcite—formed locally as gangue. Some of the quartz of the base-metal stage is cryptocrystalline and colored gray, black, or brown.

Most of the gold and silver was introduced with the base-metal stage mineralization, and veins are rarely workable where minerals of this stage are absent. In most veins, only small amounts of gold were deposited during the pyrite stage, and probably little if any gold was deposited during the uranium stage of mineralization. The gold is in part free, occurring mainly as extremely fine particles, and in part tied up in all the vein-forming minerals. The occurrence of high gold values with the base-metal sulfides and sulfosalts and of low gold values with the primary pyrite vein filling was recognized early by the miners. Subsequent studies of the distribution of gold by sampling of the vein filling and by assaying pure mineral separates (7; 6, p. 116–119) have substantiated these observations.

The interpretation of paragenesis, as presented above, differs in detail from that of Bastin (4), but in some respects is similar to the views of Alsdorf (1, p. 270), who, although he did little or no microscopic work, did have the opportunity to examine some pitchblende occurrences in the mines on Quartz Hill. Bastin had few opportunities to study the pitchblende ores in place (4, p. 4) and his studies were mostly of specimens submitted by the mining men of the district. Bastin (4, p. 5) believed "that the pitchblende was deposited during the earlier or pyritic mineralization, that it was afterward fractured, and that the fractures thus formed were filled by sulphides of the later or lead-zinc mineralization." He considered the pitchblende merely a local and unusual variation of the main sulfide mineralization of the region. Alsdorf (1, p. 270), on the basis of field examinations, noted that the "pitchblende veins are cut across, followed, and obliterated by the subsequent faulting and vein filling of the period of the precious metal veins."

Origin of Vein Types of Contrasting Mineralogy.—The pyrite and base-metal stages of mineralization were of broad areal extent and resulted in the concentric zonal arrangement of the ores of the district; the uranium stage of mineralization, on the other hand, was relatively local in extent, and the deposits formed by this mineralization do not have a definite spatial relationship to the mineral zoning. The distribution of the dissimilar types of sulfide veins can be accounted for by assuming that the source of the fluids that deposited pyrite-stage and base-metal-stage minerals was beneath the central

zone of the district, and that the fluids changed with time from predominantly iron depositing (pyrite stage) to predominantly base-metal depositing (base-metal stage). The uranium-depositing fluids can logically be assumed to have come from several local, relatively shallow sources asymmetrically arranged with respect to the dominant, deep-seated, central sulfide source.

The pyrite stage of mineralization was most intense in the central zone; to judge from the quantity of pyrite in the veins, it decreased in intensity outward from the core. Little pyrite was deposited in the peripheral zone. In the core of the central zone (Fig. 2) the veins are on the average wider than most pyrite type veins of the district, the walls are poorly defined, and the wall rock and "horses" within the veins are intensely pyritized and altered. Replacement of wall rock was an important process in the formation of these veins. Outward from the core, the pyrite-quartz veins become narrower, the walls become more distinct, and the wall rocks are less intensely pyritized. The veins outside of the intermediate zone (Fig. 2) were not filled with pyrite, and only sparse pyrite formed in the altered wall rock bounding the veins.

The minerals of the base-metal stage were deposited farther from their source than the pyrite. In the outer parts of the district, where pyrite had not been deposited in appreciable quantities, the fissures were locally filled by base-metal sulfides to yield galena-sphalerite type veins; inward from the periphery, the pyrite type veins, where reopened, were mineralized with base metals to produce composite ores.

The minerals deposited during the base-metal stage differed quantitatively from area to area but were consistent with respect to a zonal arrangement. In the central zone, where pyrite veins were reopened, copper-bearing minerals—chalcopyrite, tennantite, and locally enargite—were deposited in the openings; sphalerite and galena rarely formed in significant quantities. In the intermediate zone, as defined on Figure 2, sphalerite and galena as well as chalcopyrite and tennantite were deposited in varying proportions; and in the peripheral zone, sphalerite and galena were dominantly formed, and copper minerals were rarely deposited in commercial quantities. Gold was precipitated with the sulfides (and gangue) in all environments, but silver, mostly as sulfosalts, was deposited predominantly with the sulfides mainly in the intermediate and peripheral zones.

The uranium stage of mineralization, because it was relatively local in areal extent, formed clusters of uranium deposits, erratically distributed with regard to the mineral zoning pattern. The principal areas of uranium veins are in the Quartz Hill-Upper Russell Gulch area and the Eureka Gulch area (Fig. 2). A few deposits are present on Silver Hill and near lower Russell Gulch. This concept of the relation of uranium to hypogene mineral zoning differs from that presented previously by Leonard (11) and Armstrong (2). These writers concluded that the uranium deposits of the Central City district occurred in the intermediate zone, for at the time of their studies the known deposits (Quartz Hill) were restricted to this part of the zoning pattern.

To account for the zonal distribution of the vein types and for the textural and structural relations of the ores, it is postulated that the pyrite and base-

metal stages of mineralization resulted from fluids given off from a common, deep-seated source beneath the core of the district. Initially the fluids deposited iron, to form pyrite type veins; later they deposited copper, zinc, and lead, to produce composite veins, as defined by Bastin and Hill (6, p. 112), and galena-sphalerite type veins. The nature of the fluids changed with time, mainly at the source; and the marked change from an iron-depositing to a base-metal-depositing solution coincided with a major period of recurrent fault movement that reopened the fissures. It is the writer's belief that during the deposition of the pyrite vein filling, the channelways gradually were clogged with the material and a restraining pressure was built up on the source magma. The fault movements reopened the fissures locally and facilitated the release of the restraining pressures at depth, permitting the escape of new ore fluids into the openings. In the meantime sufficient time had elapsed to change the temperature, pressure, and composition of the ore fluid so that the openings were filled with base-metal sulfides. During the base-metal stage of mineralization, copper was preferentially deposited in openings near the apex of the source, to yield the copper-rich pyrite veins; lead, zinc, and copper in nearly equal amounts were deposited in openings farther from this source; and lead and zinc were deposited still farther out.

Contrary to observations in many zoned districts (20), there is not a complete correlation between the zonal position of the minerals and the depositional sequence, for sphalerite, which is farther from the presumed source than chalcopyrite, always is earlier than chalcopyrite in the paragenetic sequence.

Analyses of the equivalent uranium and uranium content of the porphyry sequence of early Tertiary age (16; J. D. Wells, written communication) indicate that both uranium and thorium were greatly enriched in the magma fraction that consolidated to form quartz bostonite; and these data in conjunction with the observation that the uranium deposits are closely related geographically to known exposed bodies of quartz bostonite (1, 16) are interpreted to indicate that the uranium in the vein fillings was derived from quartz bostonite magma. A mechanism to account for the uranium in a late hydrothermal phase has been suggested by Phair (16). The implication of the field and chemical evidence is that uranium-rich fluids given off by the separate masses of cooling quartz-bostonite magma moved upward along the dikes and other zones of weakness and were deposited in fissures within short distances of these channelways.

STRUCTURE OF URANIUM DEPOSITS

Pitchblende and, at places, secondary uranium minerals occur in several vein sets as local, generally small shoots or lenses. Locally the uranium ore shoots are closely related spatially to precious-metal-bearing sulfide ore shoots, but elsewhere they are isolated. Because the pitchblende formed almost wholly as a vein filling, the ore bodies were localized by structurally controlled openings.

Relation of Uranium Deposits to Fracture Sets.—Uranium deposits are present locally along four of the six principal fracture sets; no deposits have

been found, within the district, in the breccia-reef-type faults or in the north-northeast-trending fracture set. Commonly within any area of uranium deposits the metal occurs in two or more different fracture sets.

Twenty-two veins in the district contain uranium deposits of known significance or of potential importance. Ten of these deposits are in veins that trend N. 75°–80° E., five are in veins that trend N. 80°W. to N. 85° E., five are in veins that trend N. 55°–70° E., and two are in veins that trend N. 70° W. The other uranium occurrences are in the same fracture sets as the significant uranium deposits.

In both the Quartz Hill and the Eureka Gulch areas, which contain the largest number and the most valuable deposits, the uranium occurrences are along two or more fracture sets, some of which intersect. At Quartz Hill, deposits in the German-Belcher, Kirk, and Wood veins have been mined (6). At Nigger Hill, in the Eureka Gulch area (19, pl. 1), deposits occur in three different fracture sets; the deposits in each of the sets are proved or are of probable economic importance.

All the fracture sets were present before uranium stage of mineralization, with the possible exception of the north-northeast-trending fracture set—the youngest of the fractures. Mineralization of the fractures was dependent, therefore, on local openings.

Ore shoots.—The pitchblende, like the precious-metal and base-metal ores of the district, is not regularly present throughout the veins, but instead occurs in ore shoots or smaller lenses, pods, and stringers that are separated by vein filling that is essentially devoid of uranium. Within the shoots, pitchblende forms discontinuous bodies—lenses and pods—that pinch and swell. Some of these masses mined on Quartz Hill were very high in grade, but the bodies currently (1955) being mined usually contain ore that averages less than 1 percent uranium.

The ore shoots in the district are small, measuring at most a few tens of feet in maximum dimension, and a foot or less in thickness. Many ore shoots occur systematically within the vein. An example of deposits of this type in the Carroll mine on Nigger Hill, within the Eureka Gulch area, is described below.

The uranium ore shoots in the Carroll vein, a galena-sphalerite type vein that strikes west-northwest and dips about 70° NE., are arranged en echelon within a westward-plunging zone of favorable ground (or zone of ore shoots) that essentially coincides with a precious metal-base metal ore shoot (Fig. 6). Individual shoots vary somewhat in size. The largest shoot, on the 228-foot level, has a height of about 50 feet, a stope length of as much as 50 feet, and an average thickness of about 6 inches. A smaller shoot, with a maximum horizontal length of only about 11 feet, was mined east of the shaft on the 177-foot level. Other small shoots probably were mined previously farther east along the vein. It is likely that additional shoots of comparable size and shape will be found along the projection of the zone of ore shoots at greater depths.

Within the Carroll ore shoots the pitchblende occurs in seams, veinlets, and pods. The ore within the shoot on the 177-foot level occurred mainly as

a tabular layer that was 1 to 4 inches thick and as much as 11 feet long. The ore layer was about 6 inches above the vein foot wall and separated from it by radioactive gouge. In the lower part of the shoot, mined in a small underhand stope (Fig. 6), a pod or kidney of pitchblende ore 12 inches thick occurred at the junction of two 1-inch thick pitchblende-bearing veinlets; the pod plunged 18° N. 60° W. The ore within the shoot on the 228-foot level was mainly a tabular seam or sheet of varying thickness, but the ore occurred in part as pods at the junction of seams, and as crosscutting seams. Figure 7, a plan of the pitchblende-bearing vein on the 228-foot level, shows in detail

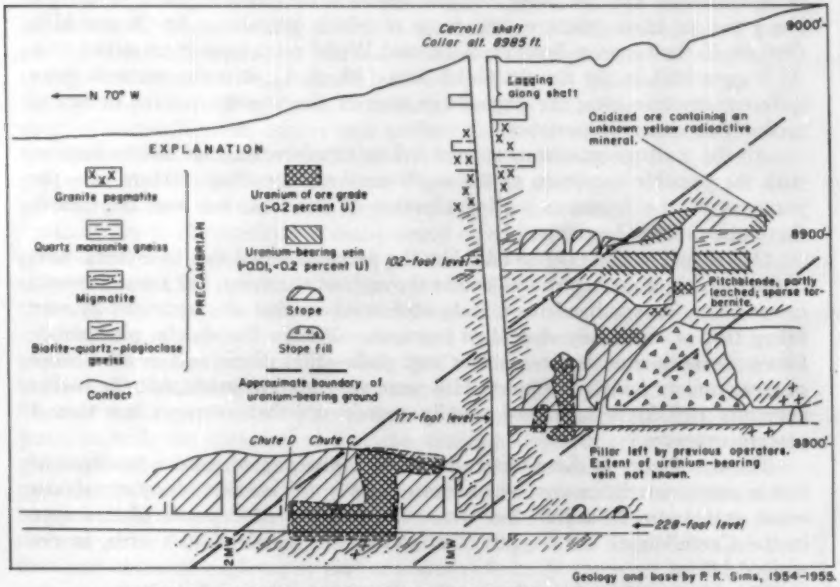
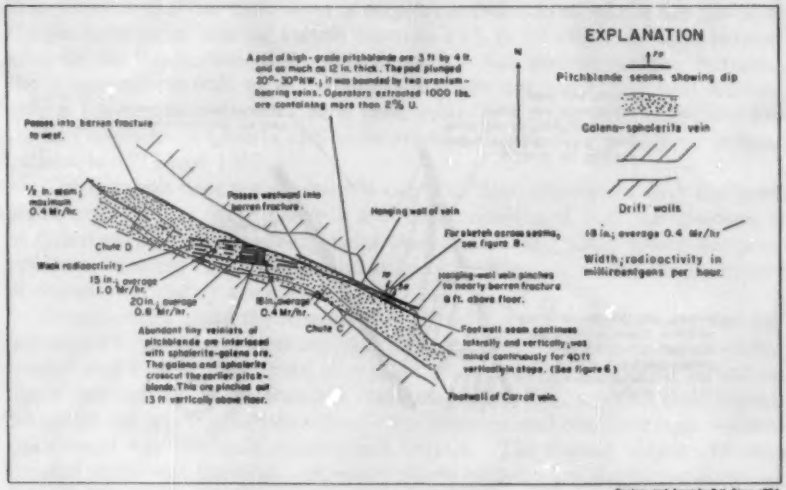


FIGURE 6—VERTICAL LONGITUDINAL PROJECTION OF CARROLL MINE, CENTRAL CITY DISTRICT, GILPIN COUNTY, COLORADO.

the pitchblende occurrences and their relation to the galena-sphalerite vein. The pitchblende near chute C was on the hanging (or north) wall of the vein, in two closely spaced seams. The outermost seam, which formed the hanging wall of the vein, pinched out within a short distance both laterally and vertically. The inner seam was more continuous and extended as a tabular layer to the top of the stope, where it pinched out. In the drift the seam was 1 inch to 3 inches thick, but it was wider in the stope, averaging about 6 inches, and at one place it was as much as 15 inches thick. Locally on the level, as shown in Figure 8, steep cross fractures between the two seams, which converge

slightly near the floor, also contained small seams of pitchblende, the whole locally constituting ore. A pod of pitchblende ore 3 feet by 4 feet by 1 foot, which occurred at the junction of the two seams, was mined opposite chute C. This pod plunged 20°–30° NW., in the same direction as the pod mined on the 177-foot level. Between chutes C and D on the level (Fig. 6) the pitchblende formed numerous, inch-thick seams that trended at an acute angle to the strike of the Carroll vein. This zone was as much as 15 inches wide; it pinched out about 5 feet above the back of the drift. The seams were cut, broken, and locally obliterated by the later galena-sphalerite ore that constitutes the bulk of the Carroll vein filling.


EXPLANATION
Pitchblende seams showing dip
Galena-sphalerite vein
Drift walls
Width; radioactivity in milliroentgens per hour.
A pod of high-grade pitchblende ore 3 ft by 4 ft and as much as 12 in. thick. The pod plunged 20°–30° N.W.; it was bounded by two uranium-bearing veins. Operators extracted 1000 lbs. ore containing more than 2% U.
Passes into barren fracture to west.
Passes westward into barren fracture.
Hanging wall of vein
Chute D
Chute C
Weak radioactivity
15 in., average 1.0 Mr/hr.
20 in., average 0.6 Mr/hr.
18 in., average 0.4 Mr/hr.
Abundant tiny veinlets of pitchblende are interlaced with sphalerite-galena ore. The galena and sphalerite crosscut the earlier pitchblende. This ore pinched out 13 ft vertically above floor.
Hanging-wall vein pinches to nearly barren fracture 8 ft. above floor.
Footwall seam continues laterally and vertically; was mined continuously for 40 ft vertically in stope. (See figure 6.)
Footwall of Carroll vein.

Geology and base by P.K. Sims, 1954.

FIGURE 7 —DETAILED GEOLOGIC MAP SHOWING PITCHBLENDE-BEARING ORE NEAR CHUTE C, CARROLL VEIN, 228-FOOT LEVEL WEST

10 5 0 20 Feet

The detailed structure of the pitchblende bodies along the veins on Quartz Hill is little known, as they were mined long ago. It is probable that most of the pitchblende occurred as small, high-grade lenses and kidneys rather than as shoots of the size of those found at the Carroll mine; possibly, however, the kidneys were sufficiently concentrated to constitute ore shoots. In the Wood vein (6, p. 245) the individual pitchblende bodies that have been mined are small and range from a few pounds to about five tons in weight. Recent exploration of the vein from the 583-foot level of the East Calhoun mine (adjacent to the Wood mine, on Quartz Hill) disclosed two small bodies of pitchblende ore, one on the level 506 feet west of the crosscut from the East Calhoun shaft and the other in a small stope above the level (9). The lenses were separated by nonuraniferous vein material. The pitchblende ore lens on

the level was 8 feet long, about 8 feet high, and 1 to 8 inches thick; it appeared to plunge about 50° W. Similarly, the deposits in the Kirk vein, which have supplied most of the uranium metal from the district, are reported (R. R. Hinckley, oral communication) to occur as small lenses, seams, and kidneys, generally adjacent to the country rock on the hanging wall of the gold-bearing

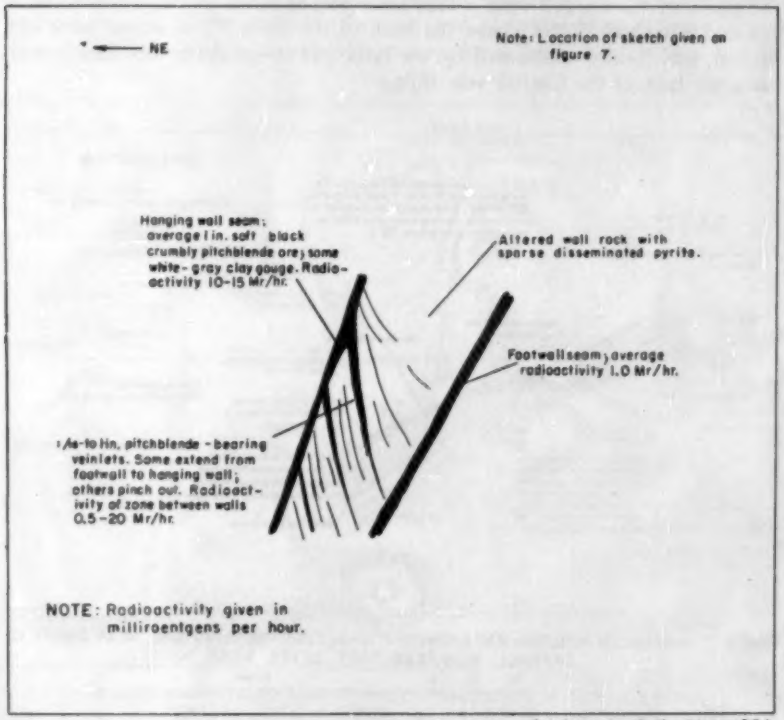

NE
Note: Location of sketch given on figure 7.
Hanging wall seam; average 1 in. soft black crumbly pitchblende ore; some white-gray clay gouge. Radioactivity 10-15 Mr/hr.
Altered wall rock with sparse disseminated pyrite.
Footwall seam; average radioactivity 1.0 Mr/hr.
1/4-to 1 in. pitchblende-bearing veinlets. Some extend from footwall to hanging wall; others pinch out. Radioactivity of zone between walls 0.5-20 Mr/hr.
NOTE: Radioactivity given in milliroentgens per hour.
Geology by P. K. Sims, 1954
0
1
2 Feet

FIGURE 8.—SKETCH SHOWING CHARACTER OF PITCHBLENDE-BEARING VEINLETS BETWEEN FOOTWALL AND HANGING-WALL SEAMS, 228-FOOT LEVEL WEST, CARROLL MINE

vein, which are separated by nonuraniferous vein material. At places the ore forms kidneys as much as a foot thick; one single piece of high-grade pitchblende ore was removed that measured 2 feet 8 inches by 1 foot (14, p. 44).

An oxidized ore shoot recently mined on Silver Hill, consisting of kasolite, metatorbernite, and meta-autunite—alteration products of pitchblende—is

structually similar to the pitchblende ore shoots. The edges of the shoot are not as sharply defined, however, as the primary ore shoots.

Localization of Ore.—The structural features which provided openings for the deposition of the metal were probably most important in the localization of the uranium deposits, but proximity of the openings to the source of the fluids also was a factor, as discussed previously. There is no direct evidence within the district that any particular type of wall rock provided a chemically more favorable depositional environment than others.

The structural features that provided openings for the deposition of uranium include: the direction and amount of fault movement, the irregularities of the fissures themselves, and the lithology and structure of the wall rocks. It is probable that the same types of structures that controlled the deposition of the precious-metal-bearing sulfide deposits (13, p. 94–99) also were responsible for the localization of uranium deposits. For various reasons, however, the structural controls of the uranium deposits are much less well known; only a few uranium deposits have been available for detailed study; the important deposits on Quartz Hill were mined out even before Bastin's investigations in 1911 and 1912.

The uranium does not necessarily occur in close association with the base-metal ores, and at many places it can be demonstrated that the uranium is in different fractures within the veins than those ores. Only where the post-uranium fractures cut or follow the uranium-bearing seams are the two types of deposits intimately associated.

Irregularities along the fissures that provided open space for uranium filling were formed at vein intersections, at the junctions of small fractures within a main vein or lode, and at the sites of small-scale deflections in strike and/or dip of the faults. At the Bonanza mine on Justice Hill, a pitchblende deposit occurs at the junction of two veins— the Bonanza and the Shamrock—where the ground was intensely sheared and broken. The deposit appears to rake parallel to the vein junction. At many places within all of the known uranium deposits the intersections of minor fractures within the veins were the loci of ore deposition, and not uncommonly pods or other enlargements occur at these junctions. Examples from the Carroll vein were given previously. The occurrences related to deflections of the filled fissures are minor and so far as known constitute small pods and lenses rather than deposits of shoot dimensions.

In some deposits it can be shown that the structure and physical character of the wall rock, rather than irregularities along the fissures themselves, were important factors in the localization of ore bodies. At the Carroll mine the zone of favorable ground (or zone of uranium ore shoots), as well as the base-metal ore shoot (Fig. 6), plunges moderately westward, essentially parallel to the trace of the intersection of the vein with the layering of the wall rocks. The wall rocks—quartz monzonite gneiss, granite pegmatite, and biotite-quartz-plagioclase gneiss—are interlayered on a fine scale. These rocks differ slightly in competence to fracturing, and the greatest weakness in this interlayered sequence occurs along the contacts. Consequently, maximum breakage and brecciation produced by the Carroll fault occurred along the intersection of

the fault with the rock layering. The position of individual en echelon uranium ore shoots, which plunge down the dip of veins, however, cannot be explained wholly on this basis; possibly they owe their position to minor deflections along the filled fault, but this has not been proved. Collins (8, p. 260–261) has noted that all the important gold ore shoots in the Nevada Gulch area, about midway between the Eureka Gulch and Quartz Hill areas, rake parallel to the intersection of the vein with the layering in the Precambrian wall rocks; and during the current studies in the Central City district the writer has found that this structural control combined with vein intersections are the two dominant factors in base-metal ore localization within the district.

U. S. GEOLOGICAL SURVEY,
DENVER, COLO.,
Sept. 14, 1956

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PEGMATITE DEPOSITS, ALTO LIGONHA, PORTUGUESE EAST AFRICA

R. W. HUTCHINSON AND R. J. CLAUS

ABSTRACT

Pegmatite bodies that contain columbite, beryl, lepidolite, bismuth and mica occur in the Alto Ligonha region of Portuguese East Africa. Pegmatites containing these minerals are restricted to belts of metamorphic schists whereas pegmatites in granitic rocks are barren.

Mining of columbite-bearing eluvial gravels derived from weathering of the pegmatites is economically feasible but exploitation of the pegmatites themselves has had limited success. A detailed study of the pegmatites was carried out to determine why pegmatite mining had proved uneconomic at depth and whether selective mining could bring about increased yields of the economic minerals. The internal structure of the bodies and the relationship of the minerals to internal structure offer a solution to these questions.

The internal structure of the pegmatites is very similar to that of comparable bodies in many districts of the United States and Canada. The same mineralogical assemblages are present and these occur in the same sequence from walls inward. This is thought to be further support for the concept of origin by crystallization in a restricted system for the zoned pegmatites. Two zones within the pegmatites of the Alto Ligonha area appear to have been formed partially by replacement, but this process has been of only minor importance in pegmatite genesis.

There seems to be a regional zoning of pegmatites in the area based on the presence or absence of lithium minerals. Pegmatites lacking lithium minerals have a simpler internal structure than lithium-bearing bodies.

INTRODUCTION

A GEOLOGICAL study of pegmatite mineral deposits in the Alto Ligonha region of Portuguese East Africa was carried out from July to December, 1953. These deposits are located in the northeast portion of the province of Zambezia, about two hundred miles west of the town and port of Mocambique (Fig. 1). The area is accessible by road from Mocambique.

The deposits studied are of two main types. The first of these are columbite-bearing gravels, both eluvial and alluvial, that have been derived from pegmatites by weathering and erosion. The second are granitic pegmatites that have been mined for beryl, lepidolite, columbite, native bismuth, and mica.

The study was aimed primarily at an economic evaluation of both types of deposit. In the case of the columbite-bearing gravels, this was a straightforward problem in mineral economics, but the evaluation of the pegmatites was more difficult. The internal structure of eight individual pegmatites was mapped in detail at scales of 1:250 or 1:500 using a plane table and telescopic alidade. Numerous others were examined but not mapped. From the de-

tailed mapping it was possible to relate the occurrence of the economic minerals to distinct lithologic and structural units within the pegmatite bodies and thereby determine whether selective mining operations could be profitably carried on.

In addition to the economic aspects of the study, certain features of scientific interest were encountered. The internal structure of the pegmatites was found to be remarkably similar to that of pegmatites in many districts of the United States and Canada. Rare-element-bearing bodies in the area occur only in metamorphic schists but pegmatites in granitic gneiss contain only

INDEX MAP SHOWING LOCATION OF ALTO LIGONHA DISTRICT PORTUGUESE EAST AFRICA

Fig. 1

magnetite. There also appears to be a regional zoning of pegmatites in the area based on the presence or absence of lithium minerals.

The pegmatite deposits, including features of both economic and scientific interest, provide the main subject of this discussion. The pegmatites studied represent only a small number of those occurring in the area, but they are believed to be typical of the rare-element-bearing bodies of the Alto Ligonha region.

Acknowledgments.—The geologic mapping and economic evaluation of the deposits was carried out for Union Carbide and Carbon Corporation,

which kindly gave permission to publish the results of the study. Special thanks are extended to Mr. D. F. Frasché of Union Carbide Ore Company, a division of the Corporation, who initiated the program. Mr. Davenport West, Jr., and the members of his staff gave invaluable assistance in matters of administration and transportation.

The writers are grateful to Dr. Enrico Gouveia Pinto of Empresa Mineira do Alto Ligonha in Lourenco Marques, Portuguese East Africa for his kind hospitality. Senhor Engineer Freitas, mine manager at Muiane, provided valuable information and assistance during the field operations. Thanks are due also to the other employees of the Empresa, whose cooperation during the field season was important to the success of the program.

The study was carried out under the supervision of Dr. E. N. Cameron of the Geology Department, University of Wisconsin, Madison, Wisconsin. Dr. Cameron visited the party in the field and offered helpful advice during the mapping and the preparation of this report.

GEOLOGY OF THE ALTO LIGONHA AREA

General Geology.—The entire northern portion of Portuguese East Africa is underlain by a large shield area of Precambrian rocks. Granite and granite gneiss predominate, but in the Alto Ligonha region, a much wider variety of rock types occurs. Here, elongated, synclinal and linear-shaped belts of medium-to-high-rank metamorphic rocks (Fig. 2) underlie large areas (1). Within these belts, quartz-biotite and quartz-muscovite schists are most abundant, but quartzites, chloritic and amphibolitic schists are also present.

Pegmatites are numerous and occur both in the granitic rocks and in the belts of metamorphic schists. A significant difference was noted, however, between pegmatites contained in these two different host rocks. Pegmatites in the metamorphic schists commonly, although not invariably, contain concentrations of beryl, columbite, lepidolite, bismuth or muscovite. Pegmatites in the granitic gneisses are barren of these rare-element minerals, but contain noticeable amounts of coarsely crystalline magnetite.[1]

All the rocks of the area have been subjected to intense lateritic weathering, and their resulting advanced state of decomposition makes geologic investigations of their mineralogy and structure difficult.

Geomorphology.—The geomorphology of the area is related to the formation of the eluvial and alluvial gravels containing columbite and, in some cases, beryl. These are the most important ore deposits of the region.

The Alto Ligonha area has rather low topographic relief with gently rolling hills and broad, low divides. These are the remnants of a mature upland surface that was developed over the entire area. Deep lateritic weathering has affected most of the surface rocks. In granitic areas, a thick mantle of sandy reddish laterite obscures fresh bedrock, while the belts of metamorphic schists are covered by dark red lateritic clays. Numerous monad-

[1] One exception is the Naipa pegmatite which contains all these minerals but lies in gneissic granite. It is, however, located almost on the contact between the gneisses and metamorphic schists.

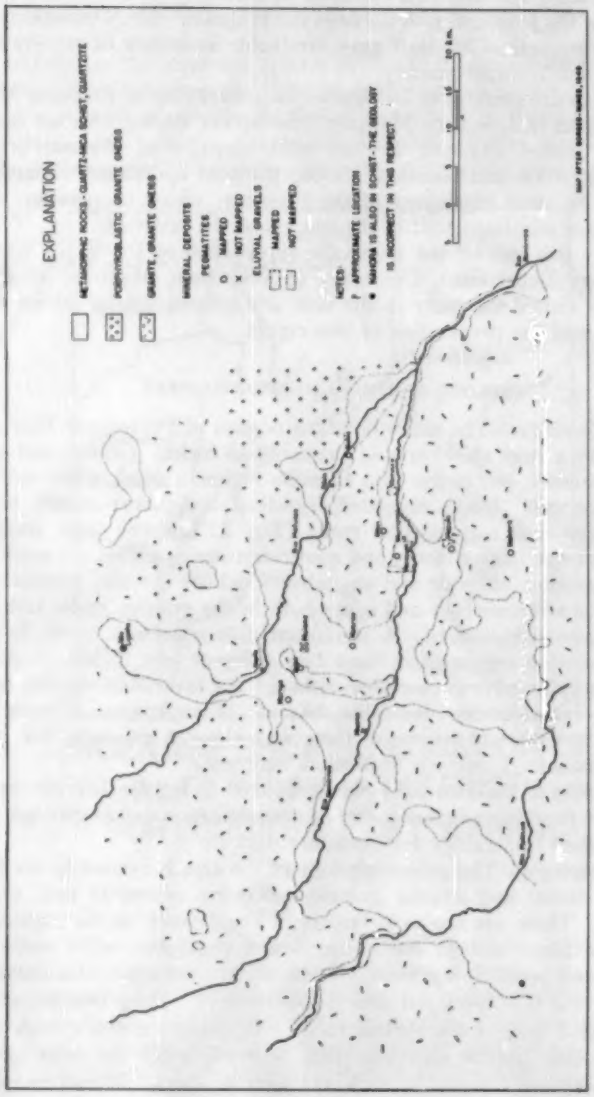

Fig. 2. GEOLOGIC MAP OF THE NORTHERN HALF OF E.M.D.A.L. CONCESSION
ALTO LIGONHA DISTRICT, ZAMBEZIA PROVINCE
PORTUGUESE EAST AFRICA

nocks of fresh granite gneiss form steep, rounded hills that rise abruptly from the weathered lateritic surface.

After the development of the mature upland topography, uplift and tilting caused a rejuvenation of streams, which are now actively dissecting the old upland surface. The larger streams have developed, and flow in broad low floodplains, whereas their tributaries are eroding the edges and slopes of the older mature surface.

In places, granite gneiss, pegmatite and quartzite have resisted both cycles of erosion and form hills up to 1000 feet in height. Eluvial gravels derived from a combination of both weathering cycles, cover their lower slopes.

The major streams follow the belts of metamorphic schists which are least resistant to weathering. Alluvial gravels are found alorg the floodplains of these streams.

Deposits.—The area is of interest primarily because of the presence of workable deposits of columbite. Beryl, lepidolite, bismuth, muscovite, gem stones and gold are also recovered from certain of the workings. The deposits are of two main types:

(i) eluvial and alluvial gravels, of which the former yield columbite and beryl, and the latter contain only columbite. One eluvial gold deposit was also being exploited at the time of the study.

(ii) rare-element-bearing pegmatite bodies that are now largely altered to masses of kaolin.

The gravel deposits are of economic importance due to their columbite content and some of them were being exploited by Empresa Mineira do Alto Ligonha at the time of the study. Work had not yet begun on the alluvial gravels. The eluvial deposits were being mined by a series of benches along the hill slopes. Gravels were trammed to loading bins on the lowest bench and from there were hauled by truck to sluices located on a nearby permanent watercourse. A columbite-rich concentrate was recovered from the sluice beds and further purified by panning and sorting.

The pegmatite bodies were a second potential source of columbite and also had yielded beryl, lepidolite, muscovite, native bismuth and gem stones. Exploitation of these deposits, however, had proved to be uneconomic in a number of cases. One purpose of this study, therefore, was to assess the economic potentialities of the pegmatite deposits. Some of the more important features of the pegmatites are discussed below.

PEGMATITES

External Structure

Size.—Pegmatites of all sizes, from very small to large, are found in the area. There is no progressive or systematic pattern to size differences, and there is no apparent size relationship between neighboring pegmatites. The smallest columbite-bearing body seen was a narrow, vein-like pegmatite slightly over 3 feet wide and of unknown length. The largest pegmatite is that at Muiane whose known outcrop area is over 3600 feet long and 1200 feet wide (Fig. 3). It is probable that this pegmatite extends for nearly a mile in

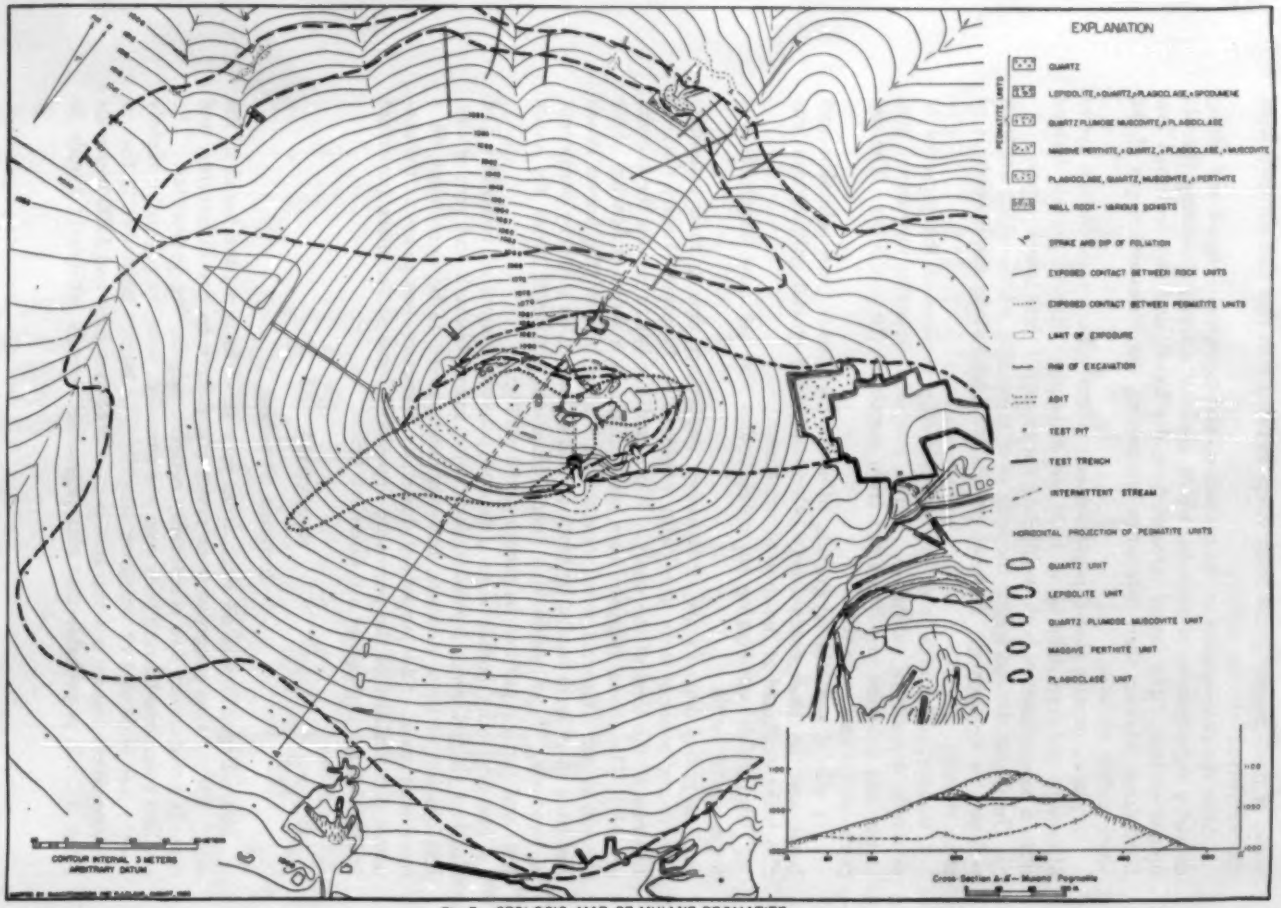

Fig. 3. GEOLOGIC MAP OF MUIANE PEGMATITE
ALTO LIGONHA DISTRICT, ZAMBEZIA PROVINCE
PORTUGUESE EAST AFRICA

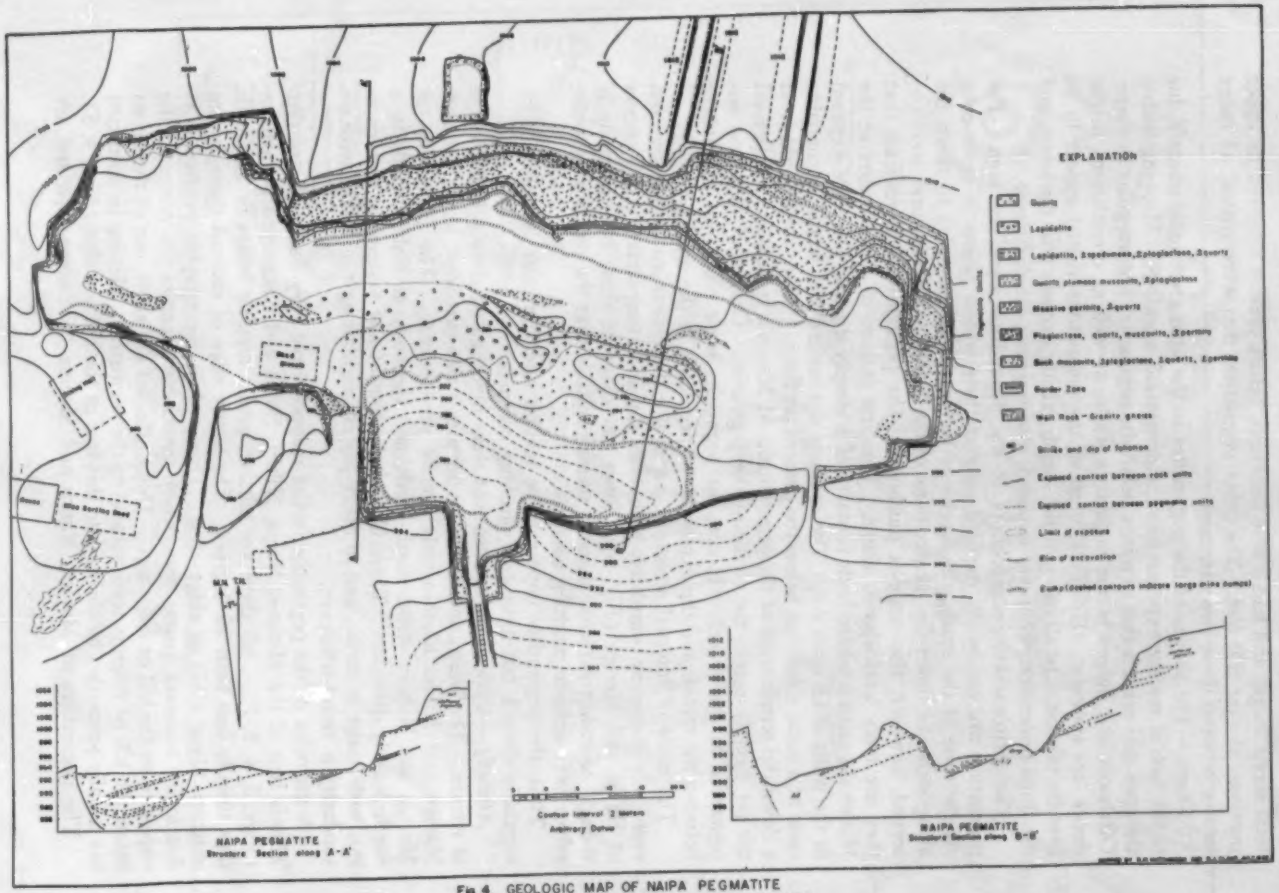

Fig. 4. GEOLOGIC MAP OF NAIPA PEGMATITE
ALTO LIGONHA DISTRICT, ZAMBEZIA PROVINCE
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total strike length and had a true thickness, before erosion removed its upper portions, of over 500 feet. The other pegmatites that were visited, all range in size between these two extremes.

Shape.—The shapes of the pegmatites in the area are mostly obscure due to the lack of surface exposures and underground workings. Mapping within the open cuts reveals that in minor detail the pegmatites are irregular in shape. Offshoots and bulges in the pegmatite walls, as well as crenulations in the floors, are common. However, most of the pegmatites visited appear to be broadly tabular. In all cases, strike length greatly exceeds true thickness, and the third dimension, wherever exposed, also suggests tabular shape.

The terminations or pinchouts of the pegmatites were not seen. The pegmatites are commonly exposed only at their widest points in open cuts. At the time of the study, the workings had not been extended to reach the along-strike or down-dip terminations of the bodies. Two features were observed, however, that suggest pinchout of the pegmatites and indicate that they are truly lenticular in shape. The first feature of these occurs at the Nanro pegmatite, where both contacts of a steeply dipping body are exposed in the walls of an open cut. The contacts dip inward and would presumably meet at a point a few feet below the present pit floor. There they would form a down-dip termination of the pegmatite. At Nanro a trench was cut beyond the pit directly across the strike of the pegmatite. Only wall rock was encountered in this trench. Hence, the pegmatite must pinch out somewhere between the trench and the exposures of pegmatite in the open pit.

The units of internal structure, especially the quartz cores, narrow and eventually disappear completely both down-dip and along-strike. This occurs at Naipa and Marige (Fig. 6). Since the shape of these internal units is thought to reflect external shape it seems probable that the pegmatites themselves have definite pinching contacts.

Thus, the pegmatites appear to be tabular and lenticular bodies with irregularly shaped, but ultimately pinching contacts.

Attitude.—Various pegmatites that were investigated show a broad range of strikes. The Naipa and Nanro pegmatites strike east-west, but at Muiane, Marige and Nihiri northeasterly trends predominate. The pegmatites at Macula and Nahora strike north-south, and the body at Nahia trends in a northwesterly direction. There is no indication of any systematic pattern in this wide range in strike, and in many places neighboring pegmatites have no similarity in trend whatever.

A majority of the pegmatite bodies mapped have very flat angles of dip. This is true of the Muiane, Naipa, Nihiri, Nahia and Nacasuppa pegmatites (Figs. 3, 4, 5, 7). All these are tabular, gently dipping lenses or sills with dips usually less than 30 degrees. The upper edge of each of these bodies outcrops along a hill or ridge crest. This positive topographic expression is due to the resistant quartz core, which invariably occupies the center of the exposure on the hill or ridge top. Due to the flat dip-angle, one of the slopes below the hill or ridge is semi-parallel to the pegmatite. Mining in open cuts has usually proceeded by slicing into this face of the hill or ridge (Figs. 4, 5).

The pegmatites at Marige, Nanro and Macula have steep dips and are

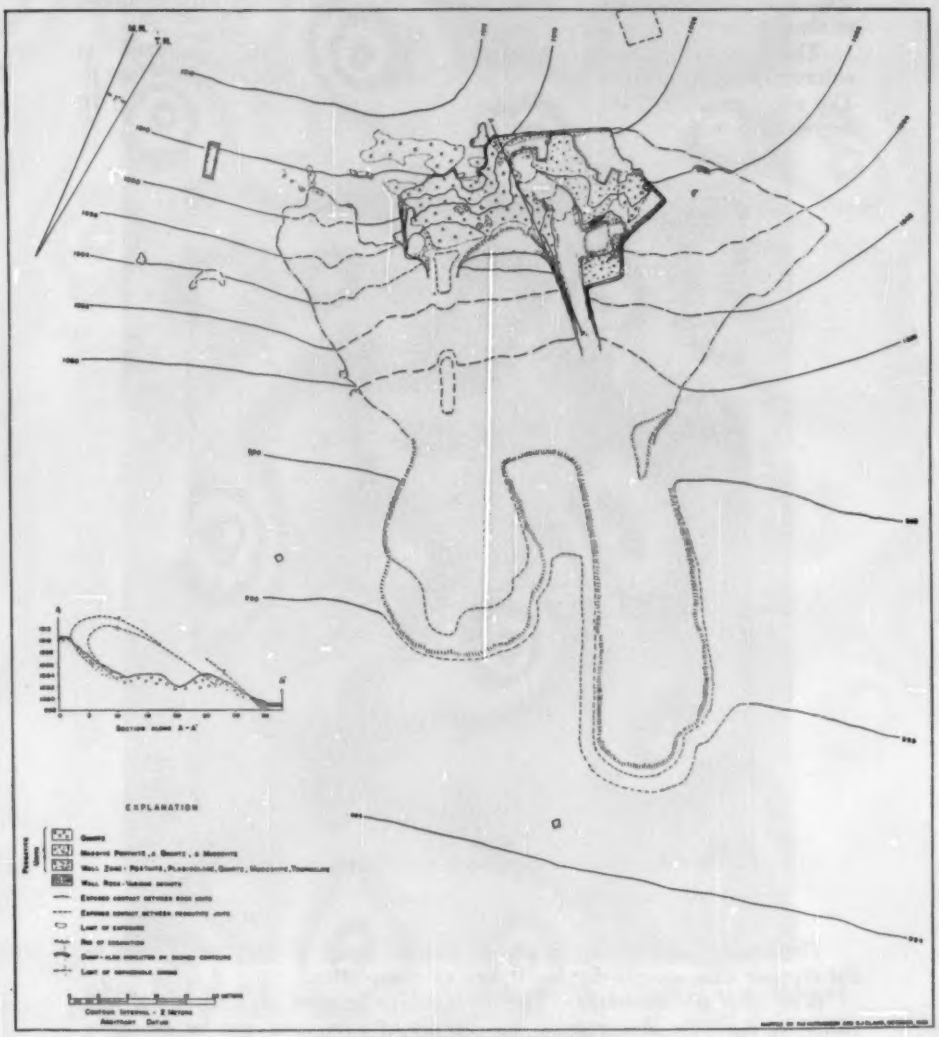

Fig. 5. GEOLOGIC MAP OF NIHIRI PEGMATITE
ALTO LIGONHA DISTRICT, ZAMBEZIA PROVINCE
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dyke-like in attitude, in contrast to the above sill-like bodies. They also outcrop along ridge tops but their topographic expression is not so pronounced as that of the flat-lying pegmatite sills.

The Nahora pegmatite is apparently a composite of the two types. It outcrops along a northerly-trending ridge and at surface dips initially at 20° E. The angle of dip becomes steeper with depth until the body dips east at 70 degrees in exposure at the pit floor (Fig. 8).

FIG. 6. Down-dip pinchout of quartz core, Marige pegmatite.

Thus, pegmatites in the area show a wide range of strikes and may be flat-dipping sills, steeply-dipping dykes, or composites.

Wall Rock Relationships.—The relationships between pegmatites and wall rocks were mostly obscured by the scarcity of exposures and by extensive decomposition wherever exposures occurred. In most places where the contacts can be seen, they are sharp and disconformable. The pegmatites transect the schistosity or foliation of the enclosing rocks (Fig. 9).

At the Nahora pegmatite it was observed that the schists immediately adjacent to the pegmatite contact were more deeply weathered than at a distance

FIG. 7. Flat dipping quartz core, Naipa pegmatite. The core is surrounded by a narrow spodumene-bearing intermediate zone.
FIG. 8. Nahora pegmatite showing increase of dip angle with depth.

of only a foot or two from the contact. This feature could be interpreted as a sign of pre-weathering wall rock alteration in the schists due to pegmatite intrusion. The effect is, however, of limited extent and importance.

Another indication of reaction between pegmatite and wall rock was ob-

served at the Marige pegmatite. Here the contact in one localized area is irregular and gradational. Tiny patches and lenses of schists are still visible within the pegmatite, and pegmatite stringers invade the schists beyond the pegmatite itself.

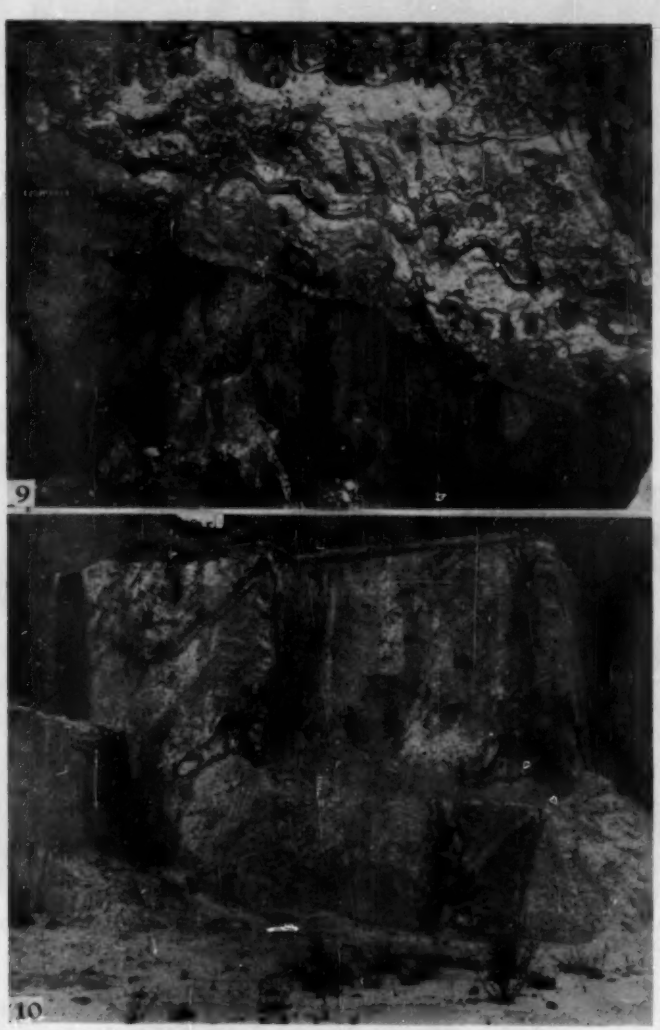

FIG. 9. Border zone at Naipa pegmatite in sharp contact with wall zone above and wall rock below.

FIG. 10. Muscovite-rich rims around huge perthite crystals, Muiane pegmatite.

The outer two zones of the pegmatites to be described below, are the only portions of these bodies that contain iron-bearing silicates. This iron may have been derived from the wall rocks through breakdown and alteration of biotite. This breakdown could have been a part of the wall rock alteration mentioned above.

No other features of the pegmatite-wall rock contacts were observed that are significant in determining the processes of pegmatite emplacement.

Internal Structure

Border Zone.—The outermost unit, or border zone, in most of the pegmatites studied is composed of sugary plagioclase, quartz, muscovite, black tourmaline and a dark-colored garnet believed to be spessartite. This unit often has a very striking appearance and texture (Fig. 9). The darker tourmaline and garnet form narrow, wavy and undulating bands within the lighter-colored groundmass of the other minerals. Between the dark bands occur broader, more persistent layers of fine, sugary plagioclase containing irregularly shaped patches of coarse-grained quartz and muscovite. The unit is readily recognized by its striking banding, by the presence of tourmaline and garnet, or by the sugary texture of its plagioclase.

Within any pegmatite, the border zone is not generally developed uniformly along all contacts. In sill-like flat-dipping bodies where it seems best developed, it is thickest along the footwall and very narrow, or absent, along the hanging wall.

In the pegmatites studied, the border zone was narrow. Its greatest observed thickness was in the Naipa pegmatite where it is 2½ feet wide along the footwall contact (Fig. 9). In some pegmatites, the border zone occurs only as a thin, one-inch selvage of tourmaline- and garnet-rich material immediately in contact with the wall rocks.

Wall Zones.—Wall zones of slightly differing composition are found in various pegmatites of the area. In the pegmatites studied, they are composed of plagioclase, quartz and muscovite, with or without biotite and perthite, and lie in contact with the inner edge of the border zone (Fig. 9). The wall zone is characterized by a medium-grained and generally equigranular intergrowth of plagioclase, quartz and muscovite. In some pegmatites, it may also contain biotite, as at Muiane and Macula. Perthite, if present, is found in abundance as large, euhedral crystals that are scattered throughout the finer matrix of plagioclase, quartz and mica. The perthite crystals often contain graphic intergrowths of quartz.

The wide range in perthite content of the zone is an interesting feature. Perthite is more abundant in the inner portions of the unit than in the outer parts. Where an intermediate zone composed of massive perthite (described below) is present, perthite is generally lacking in the wall zone. This is true in the up-dip parts of the pegmatites at Naipa, Nahia and Nihiri and to some extent at Muiane. In the lower portions of these pegmatites, the massive perthite zone is not present and perthite is abundant in the wall

zone (Figs. 4, 5). This probably is a case of downward telescoping of two units into a single zone.

The wall zone is generally the thickest unit in the zoned pegmatites and is generally symetrically developed along both sides. Unzoned bodies are composed of rock with the same mineralogic composition and texture as the wall zone. The greatest thickness of wall zone encountered was 25 feet in the Muiane pegmatite, but this is probably due to the large size of that body. At Naipa the wall zone is 8 feet thick along the footwall side of the pegmatite, and 6 feet along the hanging wall. In zoned dikes, this unit constitutes about 50 percent of the pegmatite. Where other units of internal structure pinch out, as in the down-dip parts of the Naipa pegmatite (Fig. 4), the wall zone thickens and may make up the entire body.

Intermediate Zones.—A wide variety of distinct mineralogical units occur between the wall zone and core in various pegmatites of the area. Seldom are all of these units present in any one pegmatite, and they are not uniformly and symmetrically developed. Only in the Naipa pegmatite do all the units occur. Thus, it is difficult to determine the relative positions of the various intermediate zones within a single body, but they are discussed below in what appears at Naipa to be their order of occurrence from the wall zone inward.

Book Mica Assemblage.—This unit has the same mineralogical composition as the wall zone, but it is distinguished from the latter by coarse sheets or books of muscovite up to 1 foot in diameter. This assemblage was studied[2] only in the Naipa pegmatite where it occurs symmetrically along both the footwall and hanging wall sides of the body. Here it lies, in both cases, within the wall zone and ranges between one and two feet in thickness (Fig. 4). The unit is thickest in the up-dip portions of the pegmatite but thins and disappears down-dip, apparently merging with the wall zone.

Perthite Assemblage.—All of the pegmatites studied contain an intermediate zone that is composed almost entirely of coarse crystals of perthite. Muscovite and quartz occur only in very minor amounts. Along its outer edge, the perthite assemblage lies in contact with the wall zone, and this contact is usually very sharp (fig. 11). Toward the center of the pegmatites, the perthite unit may contact any of the other intermediate zones or the quartz core depending on which units are present. This contact is commonly sharp, especially where the zone contacts the quartz core.

Dimensions of the perthite crystals vary from a few inches to several feet, and they often contain graphic intergrowths of quartz. In the Muiane pegmatite, these coarse perthite crystals in places are rimmed by a narrow 2-inch selvage of muscovite-rich rock (Fig. 10).

The occurrence and distribution of the perthite assemblage within the pegmatites of the area is an interesting and important feature. The unit is persistently developed only in the up-dip and up-plunge portions of the pegmatite bodies. Wherever the relationships were adequately exposed, the perthite assemblage was found to narrow, and often disappear completely, down-dip. In the Nahia and Nihiri pegmatites, this downward pinchout

[2] A similar zone occurs, but was not studied in detail, in the Murapane pegmatite (see Table I, Fig. 2).

of the perthite unit brings the quartz core into direct contact with the wall zone (Fig. 5).

Quartz-Plumose Muscovite Assemblage.—An intermediate zone composed of rubbly, or brecciated-appearing quartz and muscovite occurs in several of the pegmatites. Its structural position within the pegmatites is difficult to determine due to insufficient exposures and to removal of rock from the centers of the large open cuts. Where exposed at Naipa and Nahora, however, the outer edge of the unit lies in sharp contact with the

FIG. 11. Sharp contact between wall zone above and perthite zone below, Muiane pegmatite.

perthite assemblage. This relationship was also well shown in the adit at the Muaine pegmatite (Fig. 3). The inner contact of the unit is usually less distinct and may be gradational with the lithium mineral zones. In this case increasing amounts of plagioclase take the place of quartz, and muscovite decreases whereas lithium mica or other lithium minerals take its place.

The texture of this assemblage is medium-grained and equigranular, with booklets of muscovite rarely more than 1 inch in diameter. The muscovite invariably has a radiating, or plumose, habit which is a characteristic textural feature. This unit is narrow and was never found to exceed 3 feet in true

width. It is generally not continuous in all portions of any one pegmatite, but tends to be irregularly developed.

Plagioclase, Spodumene, Quartz ± Amblygonite ± Lepidolite Assemblage.—An intermediate zone containing various amounts of plagioclase, spodumene, and quartz with or without amblygonite and lepidolite is present in the pegmatites at Naipa, Muiane, Nahora, Marige and Nanro. Although somewhat variable in composition, wherever the assemblage is encountered, it is characterized by the presence of lithium minerals, especially spodumene, and by abundant plagioclase, generally the platey variety called cleavelandite. Both the spodumene and cleavelandite are completely altered to fine kaolinite. Kaolin resulting from the weathering of the plagioclase is commonly white or light gray, whereas kaolin derived from spodumene usually has a pinkish cast.

The outer contact of the unit with the quartz-plumose muscovite assemblage is often gradational. At its inner edge it commonly lies in sharp contact with the quartz core (Fig. 7).

The texture of the unit is coarse-grained. Large masses of quartz and coarse spodumene crystals occur in a somewhat finer aggregate of plagioclase, quartz and mica. At Naipa, pseudomorphs of kaolin indicate that spodumene crystals up to seven feet long were originally present. The unit is generally very narrow, and rarely exceeds 3 feet in width. It is irregularly developed within the pegmatites and seems to be restricted to the down-dip margins of the quartz cores.

The relationship between this unit and the lepidolite-albite assemblage (below) was not satisfactorily determined. Open cut mining has largely removed those parts of the pegmatites where this feature could have been studied. It seems possible that the spodumene-bearing zone is a down-dip equivalent of the lepidolite zone and results from a change in mineralogy in the deeper portions of the pegmatites. At Naipa this seems probable because the core is underlain by the lepidolite zone at the level of the present pit floor, but in a deeper cut the spodumene-bearing zone occurs along the underside of the core (Figs. 4, 7).

An amblygonite-bearing assemblage was originally present in the Nanro pegmatite. At the time of this investigation, it had been completely removed by mining, and stockpiles of amblygonite near the open cut offered the only evidence of its former existence. Little information concerning the detailed mineralogy or structural position of this unit was available. It was reported that the amblygonite-bearing portions of the Nanro pegmatite lay along the margins and downward termination of a central core of quartz. The core had likewise been removed at the time of the study. Because of their apparent similar location within the pegmatites, the amblygonite- and spodumene-bearing assemblages have been treated together in this discussion.

± Lepidolite ± Albite Assemblage.—An intermediate zone containing widely varying proportions of lepidolite and albite (cleavelandite) is present in many of the pegmatite bodies. It is the innermost intermediate zone and lies in contact with the quartz core. The lepidolite may or may not be of

commercial grade depending on the amount of albite present. In places within the Naipa pegmatite, the unit consists of almost pure lepidolite (Fig. 4). At Muiane, lepidolite and cleavelandite are mixed in almost equal proportions, while at Nahia the zone is composed of pure cleavelandite.

The texture of the unit is medium-grained although coarse, concretionary-like masses of lepidolite are common in some of the pegmatites. These are ellipsoidal in shape and when broken open are found to have a radiating columnar structure. Each tiny column is formed of lepidolite plates stacked one upon another and the columns radiate outward from the center of the lepidolite "concretion."

The lepidolite assemblage varies in width from 3 to 12 feet. It may reach even greater thickness in the large Muiane pegmatite. It is commonly irregularly developed as is the case in the Naipa pegmatite. Here it is present along the underside of the quartz core, but does not occur along the upper contact (Fig. 4). Its inner contact with the quartz core is sharp and well defined, but the outer contact of the unit with the quartz-plumose muscovite assemblage is gradational.

Core.—Most of the pegmatites studied contain a core of massive, white quartz in their central portions. The core resists weathering and invariably forms a ridge or hill crest over the up-dip extension of the pegmatite bodies. The quartz is usually massive, but occasionally coarse crystals are found in vugs or cavities within the core, or at its margins. The core varies in thickness depending, to some extent, on the size of the pegmatites. At Naipa the core is from 3 to 12 feet thick, at Nihiri and Nahia from 9 to 12 feet, and at Nahora up to 9 feet. At Muiane, the quartz core may be as much as 50 feet in thickness. The contacts of the core are almost always sharp and well defined. However, at one place in the Muiane pegmatite, a type of gradational contact was seen. Stringers and irregular patches of lepidolite-albite extend upward into the quartz core for about 6 feet. The quartz is mostly white or colorless but colored varieties are present. At the Nihiri and Nahia pegmatites, the quartz of the core in places is deep pink in color. At Naipa it is sometimes dark gray or smokey.

Relationship of Economic Minerals to Internal Structure

An important aspect of the study of the pegmatite deposits was to determine what relationship, if any, existed between the economic minerals and internal structure. If this could be established, it might then be possible to carry on selective mining within the pegmatites, thereby increasing yields of the economic minerals per ton of rock mined.

The minerals studied in this manner were columbite, beryl, lepidolite, bismuth and muscovite. It was possible to establish a definite relationship between occurrence of each of these minerals and internal structure.

Columbite.—Columbite occurs in three assemblages within the pegmatites. It is commonly present in the wall zone, in the perthite assemblage and in the quartz-plumose muscovite unit. The perthite zone, however, is the most prolific carrier of the mineral.

Small, scattered plates of columbite are present throughout the wall zone, and they become more abundant, and larger, toward the inner contacts of the unit. In the perthite assemblage, coarse columbite crystals occur in scattered, rich and often large pockets. Columbite is found also in the quartz-plumose muscovite unit, usually as fine crystals that are concentrated in small pockets.

Beryl.—Large beryl crystals had been almost entirely removed from the various mine workings at the time of this investigation. This made it difficult to establish its relationship to internal structure. At Muiane, Marige, Naipa and Nahora a few small beryl crystals were found in the perthite and quartz-plumose muscovite assemblages. At Macula and Naipa, beryl occurs in quartz at the outer edges of the quartz cores. At Nahora, in a second pegmatite, abundant large crystals of beryl were recovered along the crests of a ridge from eluvium that was almost certainly a weathered and decomposed equivalent of the perthite unit. Beryl was never found in any of the numerous exposures of border, or wall zone, nor in any of the lithium-mineral intermediate zones.

There is little doubt that the perthite assemblage is the prolific beryl-bearing unit. The quartz-plumose muscovite zone and the outer edges of the quartz core also contain minor amounts of beryl.

Beryl occurs in anhedral aggregates or masses and in fine to very coarse, euhedral crystals. The largest such crystal seen was taken from the eluvial workings at Nahora and was over a foot in diameter perpendicular to the C axis, and nearly two feet long parallel to C. Beryl varies in color from colorless to pink, green or blue. Gem varieties of the pink and blue beryl (morganite and aquamarine) are found.

Lithium Minerals.—Lepidolite and amblygonite are the lithium minerals present in pegmatites of the area. Only the former has, as yet, been of commercial value since amblygonite is rare and is present in only a single pegmatite. A third lithium mineral, spodumene, is completely altered to kaolin in all exposures but may occur at depth. All three minerals are found in the inner intermediate zones of the pegmatites.

The occurrence of lepidolite in the pegmatites of the area is repeatedly the same, and the internal structure of the bodies offers a direct guide to its location. The relationships were well exposed at Naipa, Muiane, Marige and Nahora (Figs. 3, 4). Lepidolite is found only in the innermost intermediate zone in contact with the quartz core. It may be present in a very narrow zone completely enveloping the core, but in the pegmatites studied was of commercial grade and quantity only along the underside of the central body of quartz.

Bismuth.—Native bismuth is found in small and rare but rich pockets in the pegmatites. Only two such pockets were encountered during the course of this study. At Marige, native bismuth occurred along the margins of a small pod of quartz within the perthite unit. At Naipa, a bismuth-rich pocket was found near the upper edge of the quartz core. Thus the occurrence of bismuth, so far as could be determined, seems to be spatially related to quartz pods or cores within the pegmatites.

Fine- to medium-grained aggregates of native bismuth are recovered from the pegmatites. The metal is tin-white but invariably has a surface coating of a soft, cream-to-buff colored oxidation product. The metallic nature becomes apparent when the mineral is scratched.

Muscovite.—The Naipa pegmatite was the only body mapped in detail from which commercial grade muscovite was being produced. The Murapane pegmatite also yielded ruby mica, but this body was not studied in detail. At Naipa, unflawed sheet muscovite of grade 4 specification was mined from the narrow book muscovite assemblage. Discussion of the relationships between internal structure and the occurrence of commercial mica is not justifiable on the strength of this example.

Applications of the Study to Pegmatite Mining

Mining of columbite-bearing eluvial and alluvial gravels that are derived from weathering and erosion of pegmatites provides the paying basis for the operations in the area. Mining of the pegmatite bodies themselves has been carried on intermittently for a number of years with varied success. At the commencement of the mapping program, pegmatite mining was under way only at Naipa and Marige. The operation at Naipa was possible at that time only because decreasing beryl and columbite production was being succeeded by increasing lepidolite production. Mining at Marige was a marginal operation. Exploitation of the pegmatites had proved uneconomic, and had been terminated at Muiane, Macula, Nahia, Nihiri, Nanro and Nahora. In the initial stages of development, however, all these pegmatites had given promise of profitable columbite and beryl production. The detailed study of the pegmatites was, therefore, undertaken to determine why these six operations became uneconomic. It was also intended to show whether selective mining was feasible and could improve yields of the economic minerals sufficiently to pay mining costs.

A careful study of costs and yields in pegmatite mining was made to provide a basis for evaluation of these deposits. It clearly showed that successful exploitation depended upon recovery of both beryl and columbite, or of commercial lepidolite. The other economic minerals, including bismuth, muscovite, amblygonite, and the semi-precious gem stones are of by-product importance only.

The reason for the progressive decrease in columbite and beryl production as mining proceeded, became apparent once the internal structure of the bodies was understood. The perthite assemblage was by far the most important source of both minerals. It was present, however, only in the up-dip portions of the pegmatite bodies, especially around the upper edges of the quartz core (Fig. 5). Erosion and lateritic weathering have removed the upper portions of the pegmatites so that the quartz cores now outcrop along the ridge crests or hill tops. The perthite zone was the thickest and last unit to be removed before the core was exposed. Hence the erosional remnants that now surround the outcrop of quartz at the hill crest are derived largely from weathering of this unit. They are composed of laterite, eluvium and the

remaining kaolinized parts of the perthite assemblage. Beryl and columbite, which are highly resistant to decomposition, have been concentrated in this material at the hill crest, and in gravels on the hill slopes by lateritic weathering and eluviation.

Mining, therefore, begins in weathered pegmatitic eluvium that has been enriched in beryl and columbite. It proceeds downward from the hill crest into the perthite zone which is unenriched but carries primary beryl and columbite. Eventually, mining passes out of the perthite unit due to its down-dip disappearance. Here mining has usually ceased to be profitable.

Only two zones in the pegmatites studied contained both beryl and columbite. Both minerals are recovered from the perthite and quartz-plumose muscovite assemblages, and mining should, therefore, be restricted to these units. Conversely the wall zone, which contains columbite without beryl, should not be mined unless prior sampling has indicated economic concentrations of beryl and/or columbite. None of the lithium-bearing intermediate zones examined contained beryl and columbite and should not be expected to yield these minerals in the Alto Ligonha area. Selective mining of the perthite and quartz-plumose muscovite zones, aimed at increased yields of beryl and columbite, is feasible and might make possible the exploitation of the pegmatite bodies. This, however, will be the case in initial operations on the upper parts of the pegmatites, but will probably not be possible at depth due to pinch out of the perthite zone. The quartz-plumose muscovite zone, which also contains both beryl and columbite, is present in the deeper parts of the pegmatites studied but is too narrow to be selectively mined.

If sufficient tonnages of commercial lepidolite are present, pegmatite mining can be profitably carried out. Selective mining for lepidolite has presented no problem since only one zone in the pegmatites can be expected to produce this mineral. The zone is restricted to the margins of the quartz core and especially along its lower contact. Thus, in the Alto Ligonha district, mining and exploration for lepidolite should be confined to these portions of the pegmatite bodies. In other pegmatite districts (4) lepidolite occurs in hood-like zones over quartz cores. The possibility of locating similar deposits in the Alto Ligonha area should be kept in mind in future exploration.

In order to reach the lepidolite rock, the overlying parts of the pegmatite must be removed, but this is feasible only if a sufficient tonnage of lepidolite is present. Some columbite and beryl can also be recovered in exposing the lepidolite and will help to defray costs.

GENERAL DISCUSSION

The mineral assemblages present in the pegmatites of the Alto Ligonha area are similar in composition to those present in comparable types in North America. The succession of occurrence of these assemblages from walls inward (Table I) is likewise the same in pegmatites of the Alto Ligonha area as that described from many pegmatites of North America (2, 3, 5). The significance of these features has been discussed and considered in detail by Cameron (2) and other workers. The features are believed to result from

differentiation and crystallization of a pegmatitic fluid in a restricted system. Replacement would hardly be expected to produce such consistent and repeated relationships in so many different localities. The similarity of mineral assemblages and of the sequence of occurrence of these assemblages in pegmatites from widely scattered pegmatite districts throughout the world, is one of the strongest pieces of evidence in support of this concept. The pegmatites of the Alto Ligonha area are no exception.

Replacement may, however, have contributed to the formation of two of the units of internal structure. It is thought that replacement of the wall rocks occurred at the pegmatite margins and played a prominent part in for-

TABLE 1

MINERAL ASSEMBLAGES IN PEGMATITES OF THE ALTO LIGONHA DISTRICT

	Muiane	Naipa	Marige	Nanro	Nabora	Macula	Nabia	Nihiri	Pittela	Murapaine	Nacaupa
(1) plagioclase-quartz-muscovite-tourmaline-garnet	X	X	X	X	X	X				X	
(3) plagioclase-quartz-muscovite: with or without perthite with or without biotite	X	X	X	X	X	X	X	X	X	X	X
(3a) plagioclase-quartz-book muscovite		X								X	
(3b) perthite with very minor quartz and muscovite	X	X	X	X	X	X	X	X	X	X	X
(3c) quartz-muscovite	X	X	X		X						
(5) plagioclase-quartz-spodumene: with or without amblygonite with or without lepidolite	X	X		X	X						
(8) lepidolite with or without cleavelandite and vice versa	X	X	X		X		X				
(11) quartz	X	X	X	X	X	X	X	X	X	X	X

mation of border zones. This reaction probably involved a breakdown of the minerals of the wall rocks under the influence of the injected pegmatitic fluid. Reorganization of constituents from the wall rocks together with the pegmatitic additions, then formed the border zone.

In this way it is possible to explain the high iron content of the border zone, which is in contrast with the low iron content of the remaining parts of the pegmatites. The iron has probably been inherited from reconstituted biotite-bearing wall rock. The fine-grained, sugary and equigranular texture of the border zone, which contrasts with the coarse pegmatic texture of all the other units, may also be inherited from the texture of the fine schistose wall rock, although this feature could also result from faster cooling at the pegmatite walls. The striking banded nature of the border zone may be a type of

"diffusion banding" such as Jahns has described in pegmatites of the Pala District, California (4).

At one place along the contact of the Marige pegmatite, replacement of wall rock by pegmatite almost certainly occurred. Here the contact was quite irregular and gradational. Isolated patches of schistose wall rock, retaining the same orientation as the wall rock proper, were observed inside the pegmatite for a distance of nearly 3 feet. In a similar manner, the wall rocks beyond the contact had been invaded by patches of pegmatite which did not seem to disrupt the schistosity of the enclosing schists. The border zone of the pegmatite was apparently growing by replacement at the expense of the biotite schist host rock.

Replacement may also have contributed to formation of the lepidolite-albite assemblage, which may be in part a replacement body. In some places, textures that may be interpreted as indicative of replacement were observed in this unit. In the Muiane pegmatite at the hill crest, lepidolite appears to have invaded the quartz core. Offshoots and stringers from the main lepidolite zone extend into the quartz core, and the lepidolite surrounds and embays patches of quartz. The texture suggests replacement of quartz by lepidolite. Cleavelandite appears to have replaced quartz in a similar manner in the Nahia pegmatite. In the Naipa pegmatite, where the unit contains both lepidolite and cleavelandite together, the feldspar seems to be later than, and to replace, lepidolite. Contributions to these late, soda-rich materials may have been made through the unmixing of early-crystallized potash feldspar. The significance of the concretionary-like growths of lepidolite is not understood. It is conceivable that such growth could result from either replacement or crystallization.

The pegmatites of the area can be divided into two groups depending on the presence or absence of lithium minerals. The two resulting groups correspond to a crude geographical grouping of the pegmatites. Beryllium-, columbium-, lithium-mineral pegmatites occur in the western or northwestern portions of the Alto Ligonha area, and this group includes the Nahora, Nanro, Muiane, Naipa and Marige pegmatites. In pegmatites to the southeast, lithium minerals are absent and the bodies yield only beryl and columbite. This group includes the Nahia, Nihiri and Macula pegmatites which were mapped in detail as well as the Pitteia and Murapane pegmatites which were examined less closely. Whether this feature represents a regional zoning of the pegmatite bodies or whether it reflects some basic compositional difference in the sources of the pegmatitic fluids is not known. Many other pegmatites are present in the area and additional study with this feature in mind would be worthwhile. It would certainly be of value in the future search for lepidolite deposits in the area.

CONCLUSIONS AND SUMMARY

1. Pegmatites occurring in metamorphic schists may contain columbite, beryl and the lithium minerals, whereas pegmatites lying in granitic gneiss contain only magnetite.[3]

[3] With the single exception of Naipa noted on p. 759.

2. The rare-element bearing pegmatites are zoned and contain recognizable and mappable units of different mineralogical composition and texture.

3. The internal structure of the pegmatites is very similar to that described for pegmatites in several districts of North America. The same mineral assemblages are present, and these occur in the same sequence from walls inward as is the case in comparable zoned pegmatites of North America.

4. The economic minerals in the pegmatites are definitely related to specific zones or units of internal structure.

5. Selective mining of these zones within the pegmatites can be carried out and may increase the yields of beryl and columbite per ton of rock mined.

6. Mining for beryl and columbite should be restricted to near-surface operations in the structurally higher parts of the pegmatites because the perthite zone, which is the most prolific beryl- and columbite-bearing unit, is present only in these portions of the bodies. Failure to so restrict mining in the past has led to unprofitable operations at depth, with subsequent termination of mining at several pegmatites. Mining should proceed to depth only when prior exploration by drilling or tunnelling has shown that

a) the perthite zone is continuous and of mineable width down-dip or

b) important tonnages of commercial lepidolite underlie the quartz core.

7. A regional zoning of lithium and non-lithium bearing pegmatites may be present. In view of the similarities between the pegmatites of the Alto Ligonha area and comparable types in North America, it is believed that the zoned pegmatites of the area have resulted largely from crystallization and differentiation of an injected pegmatitic fluid in a restricted system. Replacement processes have contributed to pegmatite genesis to only a minor degree, although replacement is thought to have been important in formation of the border and lepidolite-albite zones. Detailed study of the internal structure of the pegmatites provides a sound basis for economic evaluation of the pegmatite deposits.

Future exploration should be directed at the linear-shaped belts of metamorphic schists which may be expected to contain other rare element-bearing pegmatites and associated columbite-bearing gravels. Areas of granitic gneiss do not constitute favorable prospecting ground.

The grouping of lithium-bearing pegmatites to the west and northwest and of lithium deficient pegmatites to the southeast appears to be a case of regional zoning. It should be further investigated by examination of all other pegmatites in the area. Once definitely established, it should be of value in future exploration.

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THE CHEMICAL COMPOSITION OF VEIN MINERALS AND THE NATURE OF ORE FORMING FLUIDS

HEINRICH D. HOLLAND

ABSTRACT

Some relationships between the composition of aqueous solutions and the composition of solids precipitated from them are reviewed. It is then shown that, when certain conditions are fulfilled, the distribution of minor elements in vein minerals could be used to define the temperature, pressure, and chemical composition of the fluid from which precipitation took place. The possible application of this thesis to ore deposits of the Tri-State type is discussed.

INTRODUCTION

PAST thinking on the subject of the nature of ore forming fluids has followed a number of different lines. Perhaps the most elementary of these is based on the assertion that the elements found in ore minerals and those that can be shown to have been added to the wall rock surrounding ore deposits must have been present in the ore-bearing fluid. A second approach has sought to derive data on the composition of ore forming fluids by studying the chemical composition of fluids present as fluid inclusions (29, 30). A third approach has sought to define possible chemical compositions by considering the demands made on the fluid in terms of its ability to transport the elements now present as ore or gangue minerals (22, 23).

An approach which is a refinement of the first of these is suggested in this paper. The composition of the vein forming minerals is held to supply sufficient information to define fairly completely the composition of the vein forming fluid and to supply independent evidence as to the temperature and possibly the pressure prevailing during ore deposition.

RELATIONSHIPS BETWEEN THE COMPOSITION OF SOLUTIONS AND OF SOLIDS PRECIPITATED FROM THEM

Much work has been done during the past century to define the relationship between the chemical composition of precipitates and that of the solution from which they are derived. Phase diagrams for many systems in which water is the solvent have been studied at room temperature (3, 5), and silicate systems have received particular attention at high temperatures (11). From these studies data have been obtained on the incorporation of "foreign" ions in the structure of a variety of compounds, and empirical, as well as semitheoretical rules have been derived for the distribution of a "foreign" constituent between coexisting liquid and solid phases (7, 8, 16). It may be of interest to review briefly some examples of hetero-

geneous phase equilibria which illustrate principles of interest to the problem at hand.

Consider water in which are dissolved the salts A^+X^- and B^+X^-. If such a solution becomes supersaturated, one or more of the following solids may precipitate:

1. Pure A^+X^-
2. Pure B^+X^-
3. A^+X^- containing some B^+ which has substituted for A^+
4. B^+X^- containing some A^+ which has substituted for B^+
5. Compounds of the type $(A^+X^-)_m(B^+X^-)_n$
6. Hydrates of any of the above compounds

If only one of these solids precipitates, the solubility product of only that compound was exceeded. If pure A^+X^- is precipitated, then $[A^+]$, the concentration of A^+ ions, and $[X^-]$, the concentration of X^- ions in the solution in equilibrium with the solid, will be such that

$$[A^+][X^-] = K_{AX} \tag{1}$$

only an upper limit can be placed on the ratio of the concentration of A^+ to that of B^+ ions in solution on the basis of this relationship alone. On the other hand if both AX and BX precipitate simultaneously, the concentration of ions A^+, B^+, and X^- in the solution in equilibrium with the solid must obey the above relationship and a similar one relating the concentration of ions B^+ and X^- to the solubility product K_{BX}

$$[B^+][X^-] = K_{BX} \tag{2}$$

The composition of the solution can now be determined provided that K_{AX} and K_{BX} are known. Since AX and BX are the only salts in solution, it follows that

$$[X^-] = [A^+] + [B^+] = \frac{K_{AX}}{[X^-]} + \frac{K_{BX}}{[X^-]} \tag{3}$$

Thus

$$[X^-] = \sqrt{K_{AX} + K_{BX}} \tag{4}$$

$$[A^+] = K_{AX}/\sqrt{K_{AX} + K_{BX}} \tag{5}$$

and

$$[B^+] = K_{BX}/\sqrt{K_{AX} + K_{BX}} \tag{6}$$

We have thus a situation in which it is possible to define the composition of the solution from which a given pair of compounds has crystallized.

This can also be done when only a single compound crystallizes, provided that the other constituent is accommodated in solid solution within the structure of the precipitate. As an example consider the precipitation

of a compound AX in whose structure some B^+ ions have replaced an equivalent number of A^+ ions. This is illustrated by the system KBr-RbBr-H_2O in which Rb^+ and K^+ represent ions B^+ and A^+ respectively. Figure 1 shows the relationship between the mol fraction of RbBr in the solid phase and the mol fraction of RbBr in the dissolved salts, calculated from the composition of the solution by the expression

$$(\text{mol fraction RbBr})_{\text{dissolved salts}} = \left(\frac{\text{moles RbBr/liter}}{\text{moles RbBr/liter} + \text{moles KBr/liter}}\right)_{\text{solution}}$$

Figure 1 is a classical Roozeboom diagram for a system in which complete solid solution exists between two salts of the type A^+X^- and B^+X^-. It is

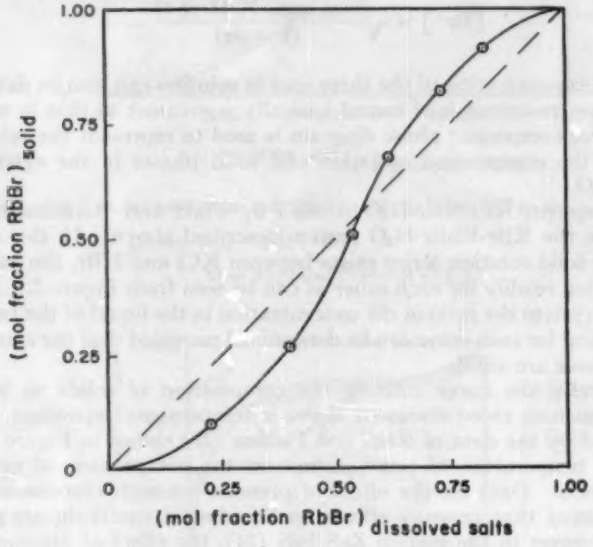


Figure 1 — Isomorphous substitution of Rb^+ for K^+ in the system KBr — RbBr — H_2O

after Durham, Rock and Frayn (10)

evident that the ratio of RbBr to KBr present in the parent solution can be determined from the composition of a (K, Rb) Br crystal provided that it is known that precipitation took place at equilibrium at 25° C at a pressure of 1 atmosphere, and that substances which might affect the relationship shown in Figure 1 are known to be absent.

Let the ratio Rb/Br determined in this way be r. Then

$$[Rb^+]/[K^+] = r \tag{7}$$

$$\{[K^+] + \alpha[Rb^+]\}[Br^-] = K_{(K, Rb)Br} \tag{8}$$

$$[Br^-] = [K^+] + [Rb^+] \tag{9}$$

so that

$$[K^+] = \sqrt{\frac{K_{(K, Rb)Br}}{(1 + r)(1 + \alpha r)}} \tag{10}$$

$$[Rb^+] = r\sqrt{\frac{K_{(K, Rb)Br}}{(1 + r)(1 + \alpha r)}} \tag{11}$$

and

$$[Br^-] = \sqrt{\frac{K_{(K, Rb)Br} \times (1 + r)}{(1 + \alpha r)}} \tag{12}$$

Thus the concentration of the three ions in solution can also be determined. The above treatment is of course basically equivalent to that in which the usual three component phase diagram is used to represent the relationship between the composition of liquid and solid phases in the system KBr-RbBr-H_2O.

The system KCl-KBr-H_2O studied by Flatt and Burckhardt (12) is similar to the KBr-RbBr-H_2O system described above. In this system a complete solid solution series exists between KCl and KBr, the two anions substituting readily for each other as can be seen from Figure 2. As in the previous system the ratio of the concentration in the liquid of the two anions substituting for each other can be determined provided that the assumptions stated above are valid.

Generally the curve relating the composition of solids to liquids in systems such as those discussed above is temperature dependent. This is illustrated by the data of Ricci and Fischer (28) shown in Figure 3 on the effect of temperature of precipitation on the composition of crystals of $(K, Tl)_2SO_4$. Data on the effect of pressure on such systems are scant. It is believed that pressure effects on liquid-solid equilibria are generally small; however in the system ZnS-FeS (24), the effect of pressure on the composition of sphalerite and pyrrhotite in equilibrium is not negligible, so that pressure effects must be considered for each system to be used in research on the chemical composition of ore bearing fluids.

When the crystal structure of two compounds A^+X^- and B^+X^- is not the same, complete solid solution between the compounds is not possible. As an example of two such compounds we may consider the pair NH_4Cl and KCl in which the former has a cubic face centered structure, the latter a cubic body centered structure. In the system NH_4Cl-KCl-H_2O (12) cubic face centered crystals consisting in large part of NH_4Cl and of minor parts of KCl, and cubic body centered crystals consisting in large part of

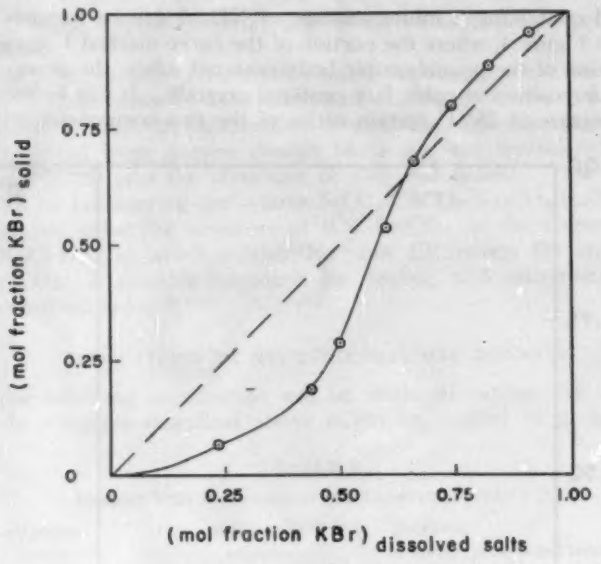


Figure 2 — Isomorphous substitution of Br^+ for Cl^- in the system KCl – KBr – H_2O
after Flatt and Burkhardt (12)

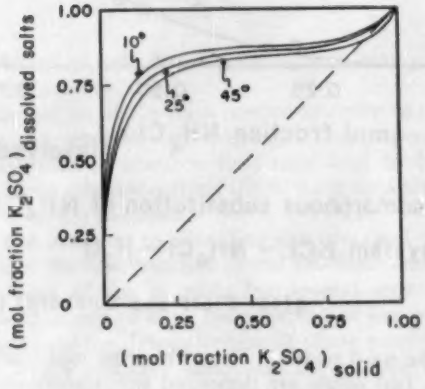


Figure 3 — Substitution of K^+ for Tl^+ in the system $Tl_2SO_4 - K_2SO_4 - H_2O$
after Ricci and Fischer (28)

KCl and containing a minor amount of NH_4Cl can be formed. This is shown in Figure 4, where the portion of the curve marked I represents the composition of the possible cubic body centered solids, the portion marked II the composition of cubic face centered crystals. It can be seen that at a temperature of 25° C certain ratios of the two components will not be

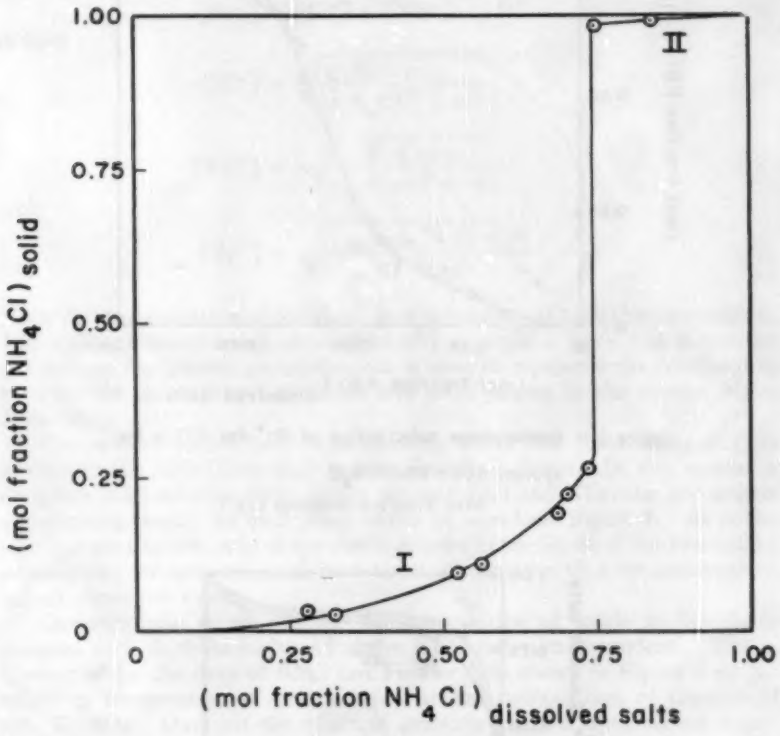


Figure 4 — Isomorphous substitution of NH_4^+ for K^+ in the system $KCl - NH_4Cl - H_2O$

after Flatt and Burkhardt (12)

encountered in the solid phase. Thus when the mol fraction of NH_4Cl in solution is 0.745, two solids are deposited simultaneously. Generally the composition of the solution at which two such solids are in equilibrium and the composition of the solids themselves are temperature dependent. If therefore such a pair of solids have precipitated together, both the temperature of formation and the composition of the solution from which precipita-

tion took place can be determined provided effects due to pressure are negligible.

In geologic systems more than three components are almost always present. The presence of such additional components may influence the relationship between the composition of a solution and the composition of solids deposited from it even though the additional components do not themselves enter into the structure of the precipitates. This might be illustrated by considering the system $SrCO_3$-$CaCO_3$-Na_2CO_3-H_2O in which Na^+ does not enter the structure of (Ca, Sr)CO_3, or the system $CaCO_3$-$SrCO_3$-NaCl-H_2O in which neither Na^+ nor Cl^- enters the structure of (Ca, Sr)CO_3. A possible approach for dealing with situations such as these is outlined below.*

APPLICATIONS TO HYDROTHERMAL ORE DEPOSITS

In the following an attempt will be made to outline the manner in which the concepts described above might be applied to determine the

TABLE 1

PRIMARY VEIN MATERIALS OF THE TRI-STATE DISTRICT (2)

Sulphides	*Sulpho-salts*	*Sulphates*
pyrite	enargite	barite (present but possible secondary)
marcasite		
chalcopyrite	*Oxides*	
millerite	quartz	
galena	chert	
sphalerite		
wurtzite (?)	*Carbonates*	
	calcite	
	dolomite	
	aragonite	

chemical composition of vein-forming fluids that have given rise to hydrothermal ore deposits.

At present almost all of the data needed in order to apply the proposed approach to a given ore body are missing. This paper, therefore, merely outlines some avenues of research that may lead to fruitful results and seeks to rectify some misconceptions which have appeared in the literature on trace elements in ore minerals.

As a particular example to illustrate the proposed approach the lead-zinc ore deposits of the type common in the Tri-State and adjoining districts may be used. This choice is made for several reasons. Firstly, these deposits have been shown to have been formed at low temperatures, a fact which should facilitate the determination of phase equilibria in the systems of interest, and which probably eliminates the complexities that are introduced by the presence of a vapor phase. Secondly, the mineral assemblage is simple and reasonably consistent over a wide area; and finally the com-

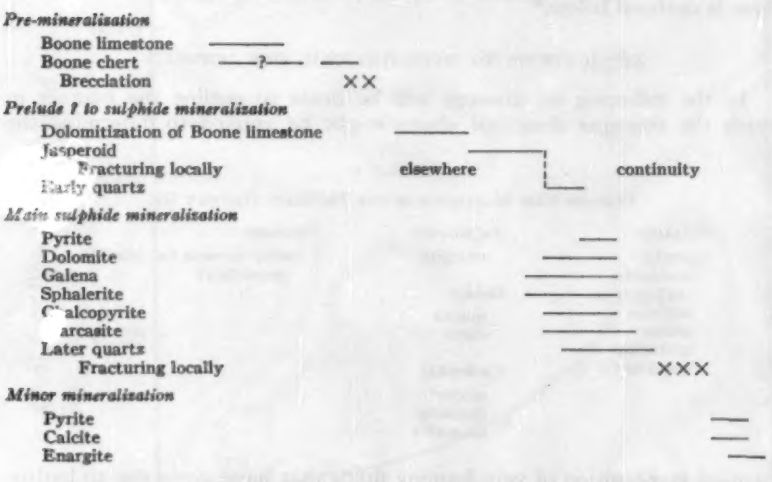
* In this treatment the concentrations rather than the activities of ions in solution are used. This approach is rigorous, but it must be remembered that the solubility products here used are not independent of the composition of the solutions.

positional variations already observed to occur in this mineral assemblage lend themselves to an analysis of the type described below. The suggested approach can be extended readily to other types of ore deposits.

Common ore minerals of the Tri-State and related districts are listed in Table 1 and the probable paragenetic sequence in Table 2. The problem consists of using the chemical composition of the vein minerals to determine the concentration of as many as possible of the elements present in the ore forming fluid during ore deposition. Let us restrict ourselves to a

TABLE 2

COMPOSITE PARAGENETIC DIAGRAM—TRI-STATE ORES (2)



vein that contains calcite, pyrite, sphalerite, galena, and barite and let us take as our working hypotheses

1. that precipitation of these minerals took place either simultaneously or that the physical conditions and chemical environment remained essentially unchanged during the precipitation of these minerals,
2. that precipitation took place from true solution at equilibrium, and
3. that the composition of the vein minerals has not changed since their precipitation.

It is not suggested here that these assumptions are necessarily valid for the Tri-State ore deposits. Indeed, the fact that barite may be of secondary origin suggests that assumption 1 may not be correct. The justification for beginning with these assumptions is that they serve as a convenient starting point, and may very well be valid at least for certain pairs of minerals occurring in ore deposits (9). Furthermore the present analysis indicates the possibility of verifying these assumptions for any

particular deposit, so that their acceptance does not represent an act of faith on the part of the investigator.

One may then write that at the time of deposition of calcite, sphalerite, pyrite, galena, and barite

$$[Ca^{++}][CO_3^{--}] = K_{CaCO_3} \tag{13}$$

$$[Zn^{++}][S^{--}] = K_{ZnS} \tag{14}$$

$$[Fe^{++}][S_2^{--}] = K_{FeS_2} \tag{15}$$

$$[Pb^{++}][S^{--}] = K_{PbS} \tag{16}$$

$$[Ba^{++}][SO_4^{--}] = K_{BaSO_4} \tag{17}$$

In the above equations there are nine unknown concentrations. Furthermore, the values of the solubility products probably all depend on the temperature and pressure prevailing during the deposition of these compounds and also on the concentration of other ions in the solution. Thus the problem is indeterminate as it stands, and additional relationships are needed in order to specify the values of the undefined variables. At least some of the necessary relationships can be derived from a consideration of the chemical composition of the vein minerals, and in particular of the distribution of the major elements of some minerals as minor elements in others. Thus calcite may contain Fe^{++}, Zn^{++}, and Ba^{++} and it is to be expected that the ratio of Fe^{++} to Ca^{++}, Zn^{++} to Ca^{++}, and Ba^{++} to Ca^{++} in calcite is related to the ratio of the concentration of these ions in solution by equations of the form

$$\frac{[Fe^{++}]}{[Ca^{++}]} = f\left(\frac{Fe}{Ca}\right)_{CaCO_3} \tag{18}$$

$$\frac{[Zn^{++}]}{[Ca^{++}]} = g\left(\frac{Zn}{Ca}\right)_{CaCO_3} \tag{19}$$

$$\frac{[Ba^{++}]}{[Ca^{++}]} = h\left(\frac{Ba}{Ca}\right)_{CaCO_3} \tag{20}$$

where f, g, and h are functions of P, T, and the composition of the vein forming fluid. Similarly barite from some localities (21) is known to contain lead, so that it is probably permissible to write

$$\frac{[Pb^{++}]}{[Ba^{++}]} = i\left(\frac{Pb}{Ba}\right)_{BaSO_4} \tag{21}$$

where i is also a function of P, T, and the composition of the ore forming fluid. Since we have introduced no new variables in equations 18–21, we have reduced the total number of unknowns considerably, but are still not able to solve for the concentration of the individual ions in the ore forming fluid.

In equations 18–21 the concentration in solution of the minor element was in all cases smaller than the concentration required to cause the precipitation of the corresponding mineral containing the minor element as the major constituent. Thus, the concentrations of Zn^{++}, Fe^{++}, Ba^{++} and Pb^{++} in solution were small enough so that the solubility product of smithsonite, siderite, witherite and cerussite was never exceeded. This is not strictly the case in the substitution of Fe^{++} for Zn^{++} in sphalerite. Although the iron sulfide, pyrrhotite, is absent from the ores, pyrite and marcasite are usually present and probably often precipitate together with sphalerite. The ratio of Zn^{++} to Fe^{++} in such cases is thus equal to that at the eutectic point between sphalerite and pyrite at the temperature of formation. Furthermore the concentration of Fe^{++} in sphalerite can be used to fix the temperature of formation of this mineral under these conditions provided the pressure is known and the effect of other ions which may substitute for Zn in sphalerite has been taken into account (24). The same is true of any such pair of compounds, and the principle underlying this method of geothermometry can be extended to a number of other systems. We can thus write

$$T = w\left(P, \frac{Fe}{Zn}\right)_{ZnS} \tag{22}$$

Unfortunately the amount of zinc which is taken into solid solution in pyrite at low temperatures is very small (13, 24), so that the corresponding relationship for pyrite is of little practical assistance.

Sulfur is present in three different forms in the minerals considered in this example: S^{--}, S_2^{--}, and SO_4^{--}. The concentration of these ions in solution is governed by the equilibria

$$2\,S^{--} \rightleftharpoons S_2^{--} + 2\,e$$
$$4\,H_2O + S^{--} \rightleftharpoons SO_4^{--} + 8\,H^+ + 8\,e$$

and is related to the redox potential, E_h,* by the equations

$$E_h = E_1^\circ - \frac{RT}{2F} \ln \frac{[S_2^{--}]}{[S^{--}]^2} \tag{23}$$

where E_1° is the value of the redox potential when $[S_2^{--}]/[S^{--}]^2 = 1$, and

$$E_h = E_2^\circ - \frac{RT}{8F} \ln \frac{[SO_4^{--}][H^+]^8}{[S^{--}]} \tag{24}$$

where E_2° is the value of E_h when $[SO_4^{--}][H^+]^8/[S^{--}] = 1$. E_h may be eliminated from equations (23) and (24), which upon rearrangement yield

$$\left(\frac{[SO_4^{--}]}{[S^{--}]}\right)\left(\frac{[S^{--}]}{[S_2^{--}]}\right)^4 ([H^+]^8[S^{--}])^4 = e^{\frac{8F}{RT}(E_2^\circ - E_1^\circ)} \tag{25}$$

* The sign convention is that of Latimer (25).

Since Ca^{++} does not enter the structure of pyrite or sphalerite to a measurable extent, the relationships that can be established between the chemical composition of the vein minerals and the concentration of the major elements of these minerals in the ore forming fluids have been exhausted. The variables then are the concentration of Ca^{++}, Zn^{++}, Fe^{++}, Ba^{++}, Pb^{++}, $CO_3^{=}$, $S_2^{=}$, $S^{=}$, and $SO_4^{=}$ the temperature, the pressure, the redox potential, and the concentration in the solution of ions other than those listed above. It is not possible to solve for these unknowns with the equations developed above.

Additional relationships can be obtained by considering the distribution of minor elements present in the solution between the minerals considered in this example. The literature on the occurrence of minor elements in the sulfide minerals here considered has been summarized recently by Fleischer (13) and the corresponding literature for the carbonates by Graf and Lamar (17). Analyses of minor elements in vein minerals from the Tri-State and related districts have been carried out by many investigators. Graton and Harcourt (18) found Fe, Pb, Cu, Cd, Ga, Ge, and In in all of their samples of sphalerite from this area and detected Mn in one of their specimens. Kullerud (24) reports Fe, Cd, Pb, Ge, and Ga in a specimen of sphalerite from Joplin, Mo. Waring (31) reported Cd and Tl in sphalerite from the Joplin district. Frondel, Newhouse, and Jarrell (14) found Ag and Cu as well as a number of other elements in galena from the Joplin area. Fleischer's summary suggests that Mn, Se, Ag, and Sn are almost always present in detectable amounts in chalcopyrite, and that Co, In, and Ni are usually present. In pryite Ni, Co, and Mn are commonly reported.

In calcite and dolomite Fe, Mn, Co, Ni, Zn, Cd, Ba, and Sr have been detected or introduced in the laboratory (17). A calcite from Joplin (6) was found to contain 0.11% MgO, 0.04% FeO, 0.04% MnO and 0.01% ZnO in addition to CaO and CO_2; and a dolomite (21) from the same area contained 0.90% FeO and 0.06% MnO in addition to MgO, CaO, and CO_2. Barite often contains Sr and Ca (21) and sometimes Mg, Fe, and Pb.

The introduction of the concentration of a minor element into the set of equations used for defining the composition of ore-bearing fluids adds a new unknown. Thus a reduction in the total number of unknowns will only result if the minor element is present in two or more minerals in the assemblage being studied. Fortunately a number of the elements listed above do occur in two or more of the common vein minerals of the Tri-State district. Thus, for instance Cd and Mn are present in sphalerite, calcite, dolomite and possibly in pyrite, and Ni and Co are present in pyrite and dolomite and probably also in calcite and sphalerite. For these elements one can thus probably write

$$\left\{\frac{[Mn^{++}]}{[Ca^{++}]} = j\left(\frac{Mn}{Ca}\right)_{CaCO_3}\right. \tag{26}$$

$$\left\{\frac{[Mn^{++}]}{[Zn^{++}]} = k\left(\frac{Mn}{Zn}\right)_{ZnS}\right. \tag{27}$$

$$\frac{[Cd^{++}]}{[Ca^{++}]} = m\left(\frac{Cd}{Ca}\right)_{CaCO_3} \tag{28}$$

$$\frac{[Cd^{++}]}{[Zn^{++}]} = n\left(\frac{Cd}{Zn}\right)_{ZnS} \tag{29}$$

$$\frac{[Ni^{++}]}{[Ca^{++}]} = p\left(\frac{Ni}{Ca}\right)_{CaCO_3} \tag{30}$$

$$\frac{[Ni^{++}]}{[Fe^{++}]} = q\left(\frac{Ni}{Fe}\right)_{FeS_2} \tag{31}$$

$$\frac{[Co^{++}]}{[Ca^{++}]} = r\left(\frac{Co}{Ca}\right)_{CaCO_3} \tag{32}$$

$$\frac{[Co^{++}]}{[Fe^{++}]} = s\left(\frac{Co}{Fe}\right)_{FeS_2} \tag{33}$$

Similar equations can be written for other minor elements that occur in solid solution in two or more of the minerals in the assemblage studied. It remains to be demonstrated how the equations derived above can be used to determine the composition of the ore bearing fluid and the physical conditions prevailing during the deposition of the vein minerals of ore deposits of the Tri-State type. Since the process involves essentially the solution of a number of simultaneous equations, a variety of approaches can be used; the one followed here is a possible alternative.

From equation (22) the temperature of formation can be determined provided that the pressure during ore deposition is reasonably well known. From the geologic setting of the Tri-State deposits it can be shown that the pressure at the time of ore deposition was probably small enough so that temperatures determined on the basis of the FeS-ZnS diagram at atmospheric pressure will be in error by only a few °C. In addition to data on the temperature of deposition from the iron content of sphalerite, additional information has been derived from the degree of filling of liquid inclusions (1, 26), a technique which is suited to low-temperature deposits of the type considered here.

If one now applies the temperature data and experimentally determined values of $E_1°$ and $E_2°$ to equation (25), one can calculate the value of the exponential on the right hand side of the equation. Further, from equations (16) and (17) it follows that

$$\frac{[Ba^{++}]}{[Pb^{++}]}\frac{[SO_4^{--}]}{[S^{--}]} = \frac{K_{BaSO_4}}{K_{PbS}} \tag{34}$$

Using equation (21), we now obtain

$$\frac{[SO_4^{--}]}{[S^{--}]} = i\left(\frac{Pb}{Ba}\right)_{BaSO_4}\frac{K_{BaSO_4}}{K_{PbS}} \tag{35}$$

From equations (14) and (15) it follows that

$$\frac{[Zn^{++}]}{[Fe^{++}]}\frac{[S^{--}]}{[S_2^{--}]} = \frac{K_{ZnS}}{K_{FeS_2}} \tag{36}$$

By combining equations (18) and (19) we obtain

$$\frac{[Zn^{++}]}{[Fe^{++}]} = \frac{g(Zn/Ca)_{CaCO_3}}{f(Fe/Ca)_{CaCO_3}} \tag{37}$$

so that

$$\frac{[S^{--}]}{[S_2^{--}]} = \frac{K_{ZnS}}{K_{FeS_2}}\frac{f(Fe/Ca)_{CaCO_3}}{g(Zn/Ca)_{CaCO_3}} \tag{38}$$

If we now substitute the value for $[SO_4^{--}]/[S^{--}]$ from equation (35) and the value of $[S^{--}]/[S_2^{--}]$ from equation (38) into equation (25), we obtain

$$\frac{K_{BaSO_4}}{K_{PbS}}\, i(Pb/Ba)_{BaSO_4}\left(\frac{K_{ZnS}}{K_{FeS}}\frac{f(Fe/Ca)_{CaCO_3}}{g(Zn/Ca)_{CaCO_3}}\right)^4 ([H^+]^2[S^{--}])^4 = e^{\frac{8F}{RT}(E_2^\circ - E_1^\circ)} \tag{39}$$

or

$$[H^+]^2[S^{--}] = A \tag{40}$$

where

$$A = \frac{K_{FeS_2}}{K_{ZnS}}\frac{g(Zn/Ca)_{CaCO_3}}{f(Fe/Ca)_{CaCO_3}}\left(\frac{K_{PbS}}{K_{BaSO_4}\, i(Pb/Ba)_{BaSO_4}}\right)^{\frac{1}{4}} e^{\frac{2F}{RT}(E_2^\circ - E_1^\circ)}$$

Since

$$\frac{[H^+]^2[S^{--}]}{[H_2S]} = K_{H_2S} \tag{41}$$

we have

$$[H_2S] = \frac{A}{K_{H_2S}} \tag{42}$$

Provided that f, g, i, and the value of the solubility products appearing in equation (39) are known, it is thus possible to derive the concentration of H_2S in the ore-bearing fluid at the time of deposition of the vein minerals. The concentration of H_2CO_3 can then be derived directly from the following considerations: The dissociation constant of carbonic acid into H^+ and CO_3^{++} can be written

$$\frac{[H^+]^2[CO_3^{--}]}{[H_2CO_3]} = K_{H_2CO_3} \tag{43}$$

Thus if we combine equations (41) and (43), we obtain

$$[H_2CO_3] = [H_2S]\frac{K_{H_2S}}{K_{H_2CO_3}}\frac{[CO_3^{--}]}{[S^{--}]} \tag{44}$$

From equations (13) and (14) it follows that

$$\frac{[Zn^{++}]}{[Ca^{++}]}\frac{[S^{--}]}{[CO_3^{--}]} = \frac{K_{ZnS}}{K_{CaCO_3}} \tag{45}$$

The ratio $[Zn^{++}]/[Ca^{++}]$ can be taken from equation (19), so that we can write

$$\frac{[S^{--}]}{[CO_3^{--}]} = \frac{K_{ZnS}}{K_{CaCO_3}\, g(Zn/Ca)_{CaCO_3}} \tag{46}$$

If we substitute this expression for $[S^{--}]/[CO_3^{--}]$ into equation (32), and use equation (30), we obtain

$$[H_2CO_3] = \frac{A}{K_{H_2CO_3}} \cdot \frac{K_{CaCO_3}\, g(Zn/Ca)_{CaCO_3}}{K_{ZnS}} \tag{47}$$

The preceding calculations only lead to numerical results if the various equilibrium constants and functions are known. A knowledge of these presupposes a knowledge of the temperature and pressure and of the composition of the ore-forming fluid of the vein minerals. In the case of ore deposits of the Tri-State type T and P are already reasonably well known. However from the foregoing discussion it is obvious that the composition of the ore-forming fluid must be complex. Yet data from analyses of liquid present in fluid inclusions (29, 30) suggest that most of the ions that have been dealt with above are present in concentrations small compared to the concentration of Na^+, K^+, and Cl^-. It is thus possible that the effect of the composition of the solution on the solubility products of the compounds considered here will be mainly due to the concentration of these three ions in the ore forming fluid. Furthermore, it is to be expected that Na^+ and K^+ exercise much the same effect, so that the effective composition of the vein-forming fluid might be replaceable by a salinity term, S, which consists of the sum of the concentration of the alkali halides in solution at the time of deposition of the vein minerals. There is some indication that the incorporation of ions in carbonates may be a function of the pH (32) so that at least two chemical variables must be determined before expressions of the type (42) and (47) can be evaluated.

It seems possible that these variables can be determined with the use of equations 18–21 and 26–33. The technique would consist of using a number of these equations to calculate the ratio of a given pair of ions in solution. Thus, the ratio $[Zn^{++}]/[Ca^{++}]$ follows from equation (19) and also from combinations of equations (26) and (27), and (28) and (29). According to equation (19)

$$\frac{[Zn^{++}]}{[Ca^{++}]} = g\left(\frac{Zn}{Ca}\right)_{CaCO_3}$$

from equations (26) and (27)

$$\frac{[Zn^{++}]}{[Ca^{++}]} = \frac{j(Mn/Ca)_{CaCO_3}}{k(Mn/Zn)_{ZnS}} \tag{48}$$

and from equations (28) and (29)

$$\frac{[Zn^{++}]}{[Ca^{++}]} = \frac{m(Cd/Ca)_{CaCO_3}}{n(Cd/Zn)_{ZnS}} \tag{49}$$

In a similar manner the ratio of $[Fe^{++}]$ to $[Ca^{++}]$ can be derived from equation (18) and by combining equations (30) and (31), and (32) and (33). From equation (18)

$$\frac{[Fe^{++}]}{[Ca^{++}]} = \left(\frac{Fe}{Ca}\right)_{CaCO_3}$$

From equations (30) and (31)

$$\frac{[Fe^{++}]}{[Ca^{++}]} = \frac{p(Ni/Ca)_{CaCO_3}}{q(Ni/Fe)_{FeS_2}} \tag{50}$$

and from equations (32) and (33)

$$\frac{[Fe^{++}]}{[Ca^{++}]} = \frac{r(Co/Ca)_{CaCO_3}}{s(Co/Fe)_{FeS_2}} \tag{51}$$

If it is now assumed that the temperature of deposition has been determined and that pressure effects are negligible for this type of situation, then the problem reduces to finding such values of the salinity, as defined above, and of the pH so that the ratios $[Zn^{++}]/[Ca^{++}]$ and $[Fe^{++}]/[Ca^{++}]$ calculated by means of the above equations agree with each other. Since there are four restricting equations and only two unknowns, the unknowns can be defined in this manner. Furthermore, since there are more restricting equations than unknowns, the validity of the assumptions made in the approach adopted here are subject to some control. Thus, if it should prove to be impossible to choose values for the salinity and pH such that the two pairs of three equations fail to yield consistent values, the assumption of the isochemical precipitation of the minerals used in this study or of our ability to reduce the effect of the composition of the ore bearing fluid to two variables may be at fault. At any rate it is of interest to know that enough relationships can be studied so that the assumptions made in this type of approach are subject to a certain degree of verification.

With a knowledge of the pH of the solution derived from equations 18, 19, and 48–51 and of the concentration of H_2S and H_2CO_3 as described above, the concentration of S^{--} and CO_3^{--} can be derived from equations (41) and (43) respectively. These concentrations in turn permit us to calculate by substitution into the appropriate equation the redox potential and the concentration of the metallic ions which have been used above.

FORESEEABLE WORK AND DIFFICULTIES

The application of the approach suggested in this paper involves the examination and analysis of vein minerals of ore deposits and a study of the

chemical equilibria which have been introduced. Work on vein minerals must combine a study of the geology of the ore deposit under observation, a study of the paragenesis of the vein minerals, and the separation and analysis of the various vein minerals. Such a program is much more extensive than the normal trace element study found in the literature [see for instance Fryklund and Fletcher (15)]. The study of the chemical equilibria is essentially an exploration of the phase relations in a multicomponent system. The number of components exceeds by far the number usually considered in silicate systems. That such a project is at all feasible is due to the probably large preponderance of water over the concentration of most other components in the ore bearing fluids, so that, at least at low temperatures the classical approach to aqueous solutions is probably valid.

Difficulties that will probably be encountered involve questions of the relationship between the times of deposition of the various vein minerals, and the possible complexities of the processes of incorporation of minor elements into solids. The latter is suggested by the complex zoning of galena in some ore deposits (14) and points to the need for a careful choice of elements for this study as well as to the need for detailed examination of the material chosen for analysis.

Finally, difficulties may arise due to the formation of metallic complexes in solution such as have been strongly suggested for mercury (9, 22) and for gold (23) and have been proposed for lead (20). The question of the presence of such complexes is certainly critical to the problem of the transport of metals in solution; it is possible that the data obtainable with the approach suggested here on the chemical composition of the ore forming fluid may in turn shed light on the possibility of metal transport by complexes which have been suggested on the basis of laboratory studies.

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"BANDED IRONSTONE" OF THE KANGARI HILLS, SIERRA LEONE

VLADI MARMO

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ABSTRACT

"Banded ironstone" occurs in the Kangari Hills in narrow layers and lenses, mainly in aluminous environment. The position of these layers is described. It has also been found that the formation of the "banded ironstone" is later than the basaltic volcanic activity, but may be to some extent contemporaneous with an acid volcanic activity. The introduction of iron is ascribed to the volcanic exhalations and its concentration into narrow layers to metamorphic differentiation.

The "banded ironstone" typically contains blue hornblende, which has been studied optically and is explained as being intermediate between common hornblende and oxyhornblende.

INTRODUCTION

In 1930, Dr. N. R. Junner discovered the Tonkolili ore deposits in the Sula Mountains, Central Sierra Leone. Since then the deposit has been prospected at intervals, and the tonnage is estimated at 100 million tons of ore with 57 percent iron (*7*).

The banded ironstone of the Sula Mountains continues as a zone, 20 km in length, within the schist belt. It resembles the "banded ironstones" and "magnetite quartzites" described from Asia, America, and other parts of Africa.

Within the Sula Mountains, the omnipresent lateritization prevents careful geological work.

The schist belt of the Sula Mountains continues southwards, and, within the Kangari Hills, "banded ironstone" occurs in several layers. There, however, the iron content is low and the lateritization is much less common than in the Sula Mountains; for that reason the "banded ironstone" of the Kangari Hills offers better opportunity for a study of the geological and genetic problems.

IRON-RICH BANDS OF THE KANGARI HILLS

Most all of the iron-rich bands of the Kangari Hills are associated with "quartzites," which contain a good deal of tuffaceous material and probably acid lavas.

The iron-bearing zone is not continuous, but consists of several narrow strips. The location of these strips is shown in Figure 1. The largest strip of "banded ironstone" is that to the East of Victoria (III of Fig. 1), which is 6.5 to 7 km long, and up to 200 to 300 m wide. Southwards it still continues to Baomahun (IV, Fig. 1) where narrow iron-rich strips are interbanded with garnet-cummingtonite schist. There, on the eastern margin of these schists, a valuable gold-arsenopyrite mineralization also occurs.

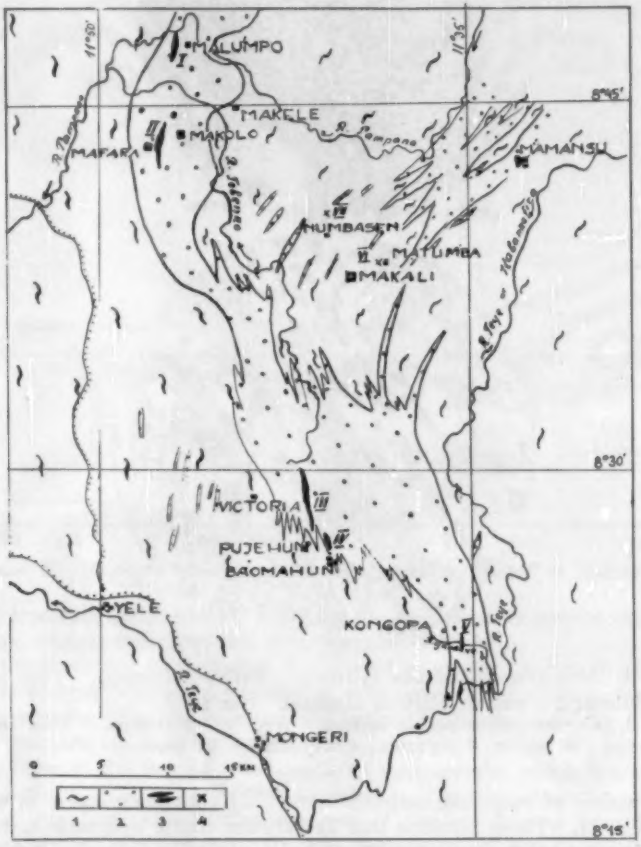


FIG. 1. Location of the "banded ironstones" of the Kangari Hills. 1 = granite, granodiorite, gneiss; 2 = schists; 3 = "banded ironstone"; 4 = patches rich in iron.

Within the granites embracing the schist belt, minor beds of magnetite quartzite also occur (VI–VII, Fig. 1).

The Malumpo Area (*I, Fig. 1*).—At Malumpo, several narrow iron-rich bands occur. They are all less than 1½ km long and 200 m wide. They

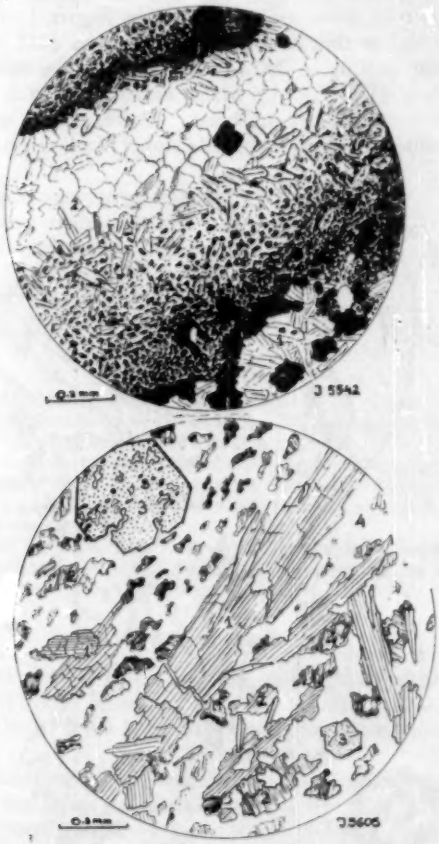
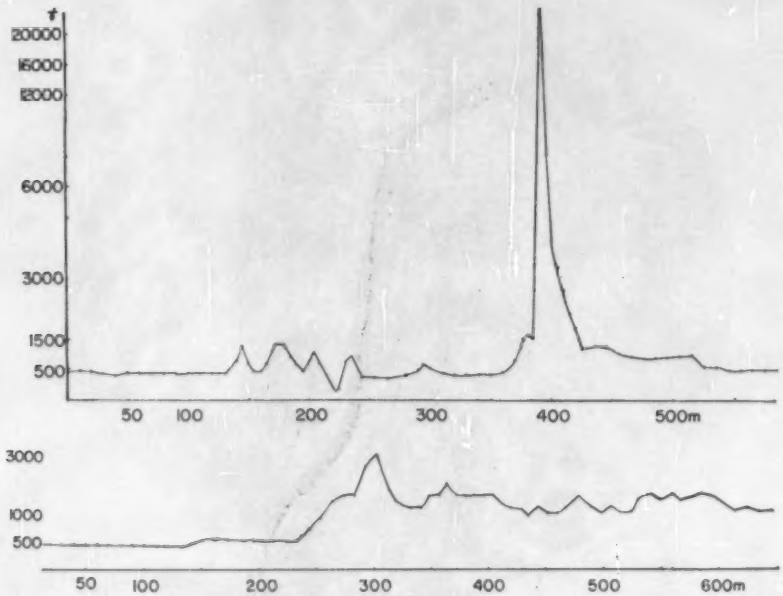


FIG. 2. Magnetite-amphibolite quartzite. SW of Malumpo. Thin section. 1 = amphibole; 2 = quartz; black is sagnetite. One nicol.

FIG. 3. Garnet-gedrite-quartz schist. SW of Malumpo. Thin section. 1 = gedrite; 2 = biotite; 3 = garnet; 4 = quartz. One nicol.

consist mainly of magnetite quartzite commonly containing layers of amphibole (Fig. 2). Those portions that lie between coarse quartzose and hornblende layers may be exceptionally rich in magnetite. These portions are also much finer grained than are the barren quartz and hornblende bands.

In the magnetite-bearing portions the garnet is sparse, but it is conspicuously abundant in the schists enclosing the iron-rich layers, and the amphibolite south of these layers contains several concordant layers, up to 300 m wide, consisting of cordierite schist ("Knotenschiefer"), and garnet-cordierite schist. There are also minor layers of micaschist containing andalusite or sillimanite and garnet; the garnet is also commonly present in the amphibolite. Consequently, the environment of the magnetite quartzite at Malumpo is rather aluminous—a feature characteristic of all iron-rich layers described below. The aluminous character of the environment is also shown in the composition of the amphibole in association with the magnetite. In Figure 3 a portion of



FIGS. 4, 5. Magnetic traverse across the "banded ironstone" at Mafara.

banded ironstone is illustrated, in which the amphibole is gedrite occurring as coarse, slightly radiating, pale dirty greenish laths.

At the north end of the layers, the banded ironstone consists of very thin layers of compact magnetite alternating with layers of hornblende-cummingtonite quartzite. The thickness of the magnetite layers is 0.1 to 0.5 mm, that of quartzite layers about 1 mm.

Southeast of the banded ironstone is an agglomerate, which is composed of a matrix of acid volcanics and of pebbles of similar material. But, in addition, there are pebbles of granite and of similar "banded ironstone" as described above. Consequently, the acid volcanicity, at least to some extent, is younger than the formation of "banded ironstone."

The Area Northeast and East of Mafara (II, Fig. 1).—Between Mafara and Makolo the area is mainly composed of garnet-cummingtonite schist, and of garnet-cummingtonite quartzite, and the rocks there are intensively banded. The layers of quartz, of quartz and cummingtonite, of cummingtonite, and of garnet and cummingtonite alternate haphazardly, and all layers contain varying amounts of magnetite. The layers are, on the average, 1 to 2 inches thick.

The magnetite is rather abundant in places, and commonly it forms minor lenses of compact ore, but only in a few places is it concentrated into large

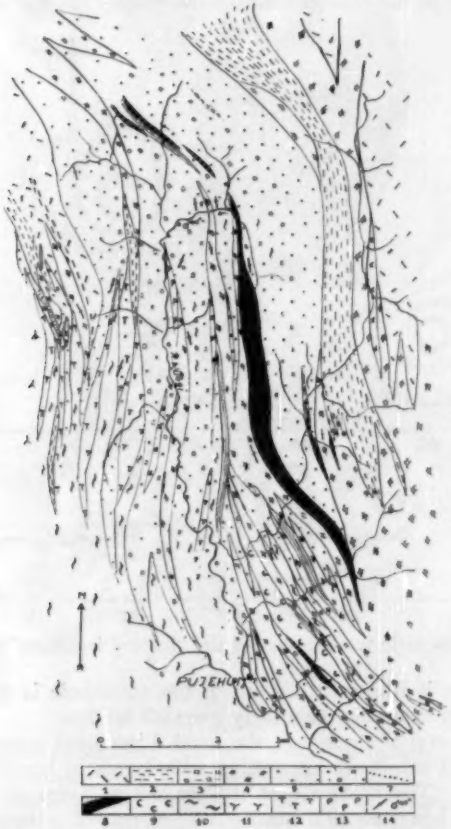


FIG. 6. Geology of the "banded ironstone" east of Victoria. 1 = tremolite serpentinite; 2 = tremolite schist; 3 = garnet-bearing tremolite schist; 4 = amphibolite; 5 = quartzite and acid volcanics; 6 = garnet-bearing quartzite; 7 = fuchsite quartzite; 8 = "banded ironstone"; 9 = cordierite schist; 10 = gneiss; 11 = granodiorite and granite; 12 = tourmaline granite (and -pegmatite); 13 = pegmatite; 14 = strike with vertical dip; pitch of fold axis.

magnetite layers, the largest of which is 30 to 100 feet thick. In Figure 4, two magnetometric traverses across this formation are shown (Finnish hand magnetometer of Arvela). The form of these traverses indicates the distribution of magnetite; the upper graph also indicates clearly the exceptionally iron-rich layer.

North of the Kruma the aluminous schists die out and amphibolite predominates. To the south of this section, on the contrary, the garnet-cummingtonite schist predominates, and there the amphibolite beds are negligible.

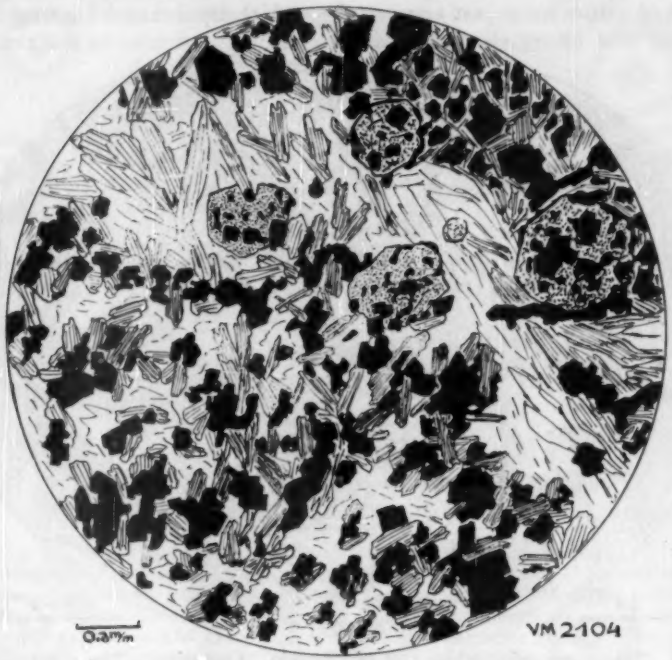


FIG. 7. Garnet-cummingtonite-magnetite schist containing blue amphibole. North of Pujehun. Thin section. One nicol.

The hornblende of the amphibolite, and of the iron-free hornblende schist, is a dull yellowish green common hornblende, but it is entirely different in portions that are rich in magnetite. There, in thin sections, it is bluish green or greenish blue and strongly pleochroic (X = pale greenish yellow; Y = yellow-green; Z = indigo blue). This blue hornblende will be discussed later.

"Banded Ironstone" East of Victoria (*III–IV, Fig. 1*).—The main band of this area is 7 km long and, on average, 200 to 300 m wide. At both ends of this band there are some other bands that may be up to 1 km long and up to 100 m wide (Fig. 6).

To the East, the "banded ironstone" grades into amphibolite and into amphibole schist; the latter is about 500 m wide. To the West, the iron-rich formation borders upon rocks consisting mainly of quartzitic material with much tuffaceous and acid volcanic elements. This zone is garnet-bearing, and it is 1 km wide.

To the South, 1 km from the "banded ironstone," southeasterly stretching layers of cordierite-biotite (-garnet-sillimanite-) schist occur. They are several kilometers in length and commonly more than ½ km in width.

To the West, farther away from the "banded ironstone," there are several bands of tourmaline-garnet granite (also at Malumpo), and 3 km west of the

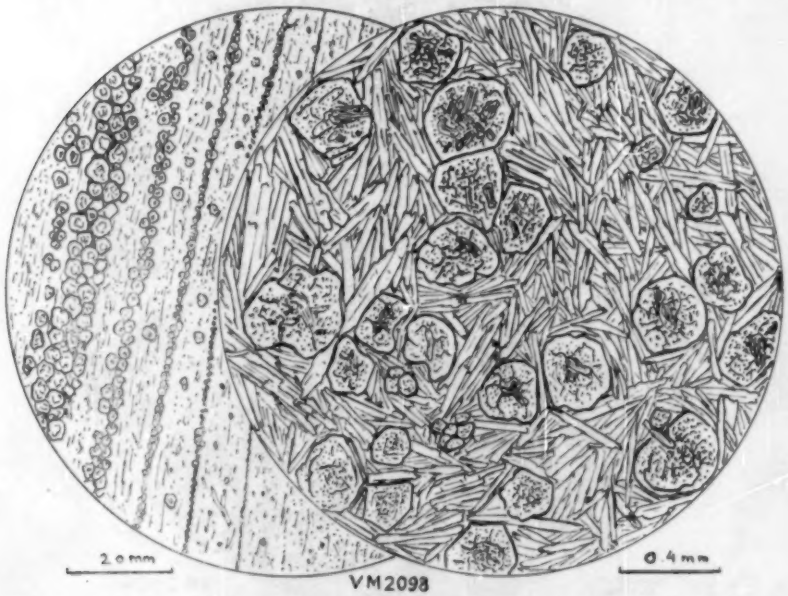


FIG. 8. Garnet-tremolite schist east of Victoria. One nicol. The right part of the figure is magnification of a detail of the left part.

magnetite-rich schists where a 40 to 50 m wide band of peculiar fuchsite quartzite occurs, associated with coarse pyrite mineralization along its eastern margin.

Southeast of Pujehun and near Baomahun magnetite-rich layers also occur, but there they are interbedded with garnet-cummingtonite schist.

As already mentioned above, here also the environment of the "banded ironstone" is rather aluminous. Most quartzites to the west of the "banded ironstone" contain garnet; commonly they also contain sillimanite or andalusite, and also staurolite in a few places. The amphibolite accompanying the "banded ironstone" is in all cases garnet-bearing.

The gradation of the "banded ironstone" into amphibole schist (and into amphibolite) takes place by gradual decrease of magnetite in the former. The amphibole of the latter rocks consists of blue hornblende and of cummingtonite. The garnet is generally fine-grained in the portions rich in magnetite, but may form crystals up to 1 cm across in the portions containing only a little or no magnetite. The garnet is almandine (n = 1.825). In "banded ironstone" it is commonly heavily contaminated by magnetite (Fig. 7), but outside of magnetite-rich portions it is well developed and occupies narrow bands (Fig. 8).

Figure 9 illustrates the cummingtonite-garnet-magnetite schist, and three features attract attention: 1, the garnet has obviously grown later than the

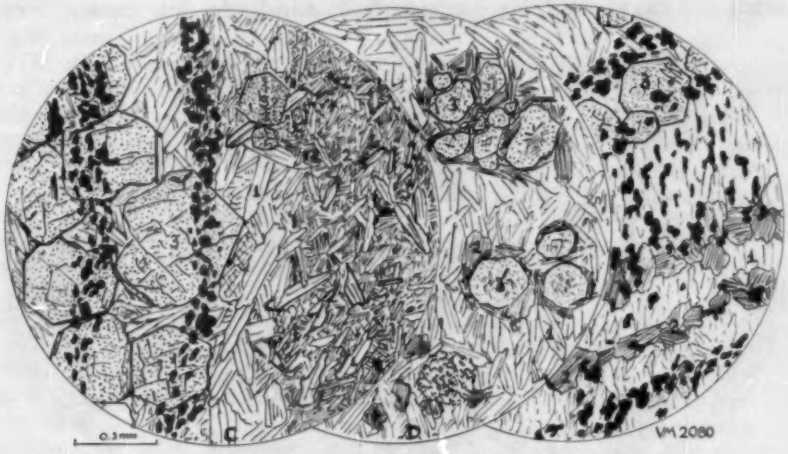


FIG. 9. Rocks associating the "banded ironstone" east of Victoria. C: garnet-cummingtonite-magnetite schist. Garnet has grown across a magnetite strip. D: garnet enveloped in a shell of biotite and hornblende. VM 2080: bedding indicated by biotite, hornblende, and garnet affected by a shearing, almost vertical to the bedding, portrayed by elongation of quartz and magnetite grains. Thin section. One nicol. 1 = cummingtonite; 2 = biotite and hornblende; 3 = garnet; black = magnetite.

magnetite (c, Fig. 9); 2, the shearing commonly cuts the bedding (rightmost section of Fig. 9), and the former appears in the orientation of quartz and magnetite grains; 3, the garnet is commonly enclosed by a mixture of chlorite and biotite (d, Fig. 9), and there may also be seen grains of entirely resorbed garnet.

As one can see from Figure 8, the garnet is obviously of sedimentary origin. From the distribution of the grain size of the garnet one can conclude that the top of the layers is to the west, and, consequently, the "banded ironstone" is younger than the amphibolites (with pillow lava structure) to the east of the magnetite-rich zone.

500 m west of the "banded ironstone," there is a zone 200 m wide showing faint conglomeratic structure. This zone also contains fairly large (up to ½ m in diameter) clusters of amphibolite in random distribution and generally distant from each other. The cobbles much resemble the amphibolite to the east of the "banded ironstone," which there forms a zone 3 km wide with beds of pillow-lavas, which are definitely of ancient basaltic lava origin. Consequently, also these amphibolite clusters may well be ejecta embedded into sandy to tuffaceous sediments.

Because the sedimentary rocks to the west of the "banded ironstone" are younger than the amphibolites, one may assume that despite the fact that most of the basaltic lava flows had occurred before the main sedimentation had begun, the basic volcanicity did not cease entirely but still continued while sands and clays were being continuously deposited. In such circumstances

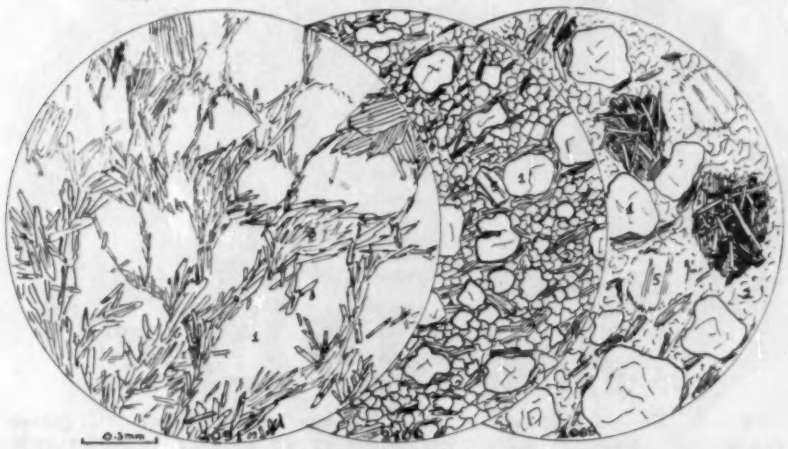


FIG. 10. Rocks associating the "banded ironstone" east of Victoria. VM 2091: amphibole quartzite. VM 2100: quartz-plagioclase porphyry. VM 2089: quartz-plagioclase porphyry containing biotite clusters penetrated by laths of muscovite. 1 = quartz; 2 = mixture of quartz and sericite; 3 = greenish amphibole; 4 = biotite; 5 = plagioclase; 6 = muscovite.

the volcanic exhalations may have been rather abundant, and they may well be responsible for the introduction of the iron of "banded ironstone."

As mentioned earlier, the "quartzites" close to the "banded ironstone" are not true quartzites, but contain much tuffaceous and volcanic elements. This suggests that they also may have received volcanic contributions during the accumulation of their sands. Such elements of "quartzites" are shown in Figure 10. VM 2091 is an amphibole quartzite in which the ordinary hornblende is cementating the rounded quartz grains. In VM 2100 and VM 2089 a texture of typical plagioclase-quartz porphyry is seen. These representatives are typical of the narrow zone separating the "banded ironstone" zone

from the main amphibolite area. All such rocks may contain garnet as well. Such structures strongly suggest the appearance of acid extrusives after the main basaltic lava flows had ceased.

The acid tuffs during recrystallization attained a texture undistinguishable from that of the ancient rhyolitic lava flows. Furthermore, the acid tuffs commonly occur in association with basaltic lava flows, but rhyolitic lavas are comparatively rare. Within the Kangari Hills definite are dikes of granite porphyry, which in both texture and structure are similar to certain portions of the above-mentioned "quartzites." This suggests that there have been both acid tuffs and also lava flows of rhyolitic to dacitic composition. On the other hand, the regular distribution of garnet rather suggests the intermixing of extrusive materials with depositing clays, and that, consequently, the acid volcanicity must have been weak if compared with that of preceding basaltic flows.

The ancient evolution of the area containing "banded ironstone" at Victoria can be reconstructed from the observations described above: After the main submarine volcanic activity (pillow lavas) producing basaltic flows had ceased, it was followed by minor acid extrusions producing acid tuffs and lavas. The period of acid extrusives was often interrupted (sandy interlayers). At the final stage or during this activity, iron-rich exhalations appeared, and they supplied the material, which during the regional metamorphism gave rise to "banded ironstone." At this time, also continuous deposition of clay and sand sediments seems to have begun.

During the regional metamorphism (period of mountain folding) the basaltic lavas have been converted into amphibolites, and the intermingled clays, sands, acid tuffs and acid lavas gave rise to the rocks associated with the "banded ironstone." Particularly the formation of garnet-cummingtonite schists (which commonly grade into "banded ironstone") postulates an abundance of magnesia and lime. The former may have derived from volcanic extrusives, the latter probably is due to the presence of ancient dolomitic interlayers.

Thus, one can understand that there are both sedimentary and volcanic features present in the "banded ironstones."

The Area near Kongopa (V, Fig. 1).—Along the Yandeye river the garnet-bearing gneiss includes the layer of "banded ironstone." The length of this layer is less than 1½ km, and its north end lies within amphibolites. The iron-rich strip consists of magnetite-hornblende schist, which commonly grades into magnetite quartzite, and generally contains garnet.

DISCUSSION

In Table I, the chemical composition of some "banded ironstones" of the Sula Mountains is given. Their composition is compared with that of a ferruginous mudstone and of marine marlstone (3).

Table I shows that the "banded ironstone" in the Tafali River may well have originated from a marine sediment intermediate between the ferruginous mudstone and the marine marlstone.

The iron necessary for the formation of true "banded ironstone" must, however, be introduced from outside. In the case of the iron-layer strip E of Victoria, the presence of acid volcanism suggests its introduction due to volcanic exhalations. The same explanation obviously applies to the "banded ironstones" at Malumpo, Mafara and Kongopa as well.

Another question raised is how the surplus iron was concentrated into narrow seams and layers. At Mafara, especially, the interbanding of magnetite seams with garnet-cummingtonite, with quartz-cummingtonite, and with quartz bands is very intricate. As shown by the microscope, there are alternating layers of quartz, of cummingtonite, and of garnet, as well as of magnetite, together with bands consisting of the several constituents mentioned above.

TABLE I

CHEMICAL COMPOSITION OF TWO "BANDED IRONSTONES" OF THE SULA MOUNTAINS AND OF MUDSTONE AND MARL SEDIMENTS

	1 Iron ore of the Simbili, the Sula Mts.*	2 "Banded ironstone" of the Tafali River	3 Ferruginous mudstone, Michigan	4 Marine marlstone, Ohio
SiO_2	22.31	56.71	52.85	46.12
TiO_2	0.15	0.30	0.60	0.78
Al_2O_3	4.65	10.70	8.71	12.80
Fe_2O_3	63.93	9.06	24.03	1.60
FeO	1.82	12.16		3.25
MnO	0.47	0.28	1.10	0.09
MgO	0.44	2.08	2.87	2.55
CaO	0.18	4.91	0.10	10.77
Na_2O			1.48	0.60
K_2O			1.89	3.60
H_2O+			5.56	3.25
H_2O-				1.70
P_2O_5	0.08	0.13	0.78	0.65
CO_2			0.20	9.19
S	0.04	0.15	0.03	0.88
SO_3				0.24
	94.07	96.48	100.20	100.30

1 and 2: analyst John Middleton (incomplete analysis).
3: Pettijohn, 1949, p. 287. Contains stilpnomelane.
4: Pettijohn, 1949, p. 287.

* The preponderance of hematite over magnetite in this ore is due to lateritization.

Under such circumstances, the most probable explanation seems to be that of enrichment due to metamorphic differentiation.

It is customary to compare described one's areas with similar areas from other parts of the world. The "banded ironstones" of Central Sierra Leone may be compared with the "banded ironstones" of East Africa. Pulphrey (4) described the banded ironstone of the central Kavirondo, Kenya. There, according to Pulphrey, the "quartzites" associated with the iron-rich portions are not quartzites at all (4, p. 10): ". . . The writer is inclined to believe that the Somia Hills quartzites represented profoundly altered acid lavas and tuffs" and: "this would appear to indicate that the quartzites were al-

tered to the form we now know within the volcanic period, and probably that they represent non-sequences of considerable duration."

Stockley (5, p. 18–19) considers that the banded ironstones of the Musoma District, Tanganyika, are normal sediments, but among the banded ironstones and jaspilites of the Musoma Series (Upper Basement Complex) he has observed gradual transition from acid lavas to the banded ironstones. This is similar to the "banded ironstone" of the Kangari Hills.

The iron formation of the Bomi Hills, Liberia (6) contains abundant cummingtonite; its microscopic features are very similar to that of the Central Sierra Leone iron formation. The writer made a short visit to Bomi Hills in 1956 and observed the striking similarity between the ore of the Bomi Hills and the "banded ironstone" of the Sula Mountains and Kangari Hills. Also, seams of garnet-cummingtonite schist occur there, and the enrichment of iron to form narrow lenses and seams in both occurrences is very similar.

The unusual blue hornblende has been mentioned above. Similar hornblende was also seen by the writer in thin sections of the iron-ore of the Bomi Hills, and it is obvious that such hornblende is typical of many similar iron formations. Information about the mineralogy of "banded ironstones" is comparatively sparse in the literature. Lamey (2) has observed the blue hornblende in the Negaunee iron formation. He writes (p. 254): "Banded ironstone consists of quartz, magnetite, and a peculiar amphibole showing low extinction (8° to 12°) and pleochroism in blue and green, others consist of garnet, others of grunerite, and still others of magnetite." According to Lamey, this amphibole does not contains any soda, and it has also been noted, by the same author, in the Vulcan formation (p. 256).

At the request of the author, Mrs. Toini Mikkola (Geol. Survey of Finland) made some optical determinations of this blue hornblende that is so typical of the "banded ironstones" of the Kangari Hills. The optical properties of this hornblende vary considerably: That from Victoria has $2V_\alpha = 60°$, $c \wedge \gamma = 13°$; from Mafara, $2V_\alpha = 64°$, $c \wedge \gamma = 15°$; from Malumpo, $2V_\alpha = 74°$, $c \wedge \gamma = 8$–$9°$. The refractive indices of the blue hornblende at Victoria are $\alpha = 1.671$; $\beta = 1.685$; $\gamma = 1.697$. These optical properties suggest that this amphibole is intermediate between common green hornblende and oxyhornblende.

The cummingtonite at Victoria has $+2V = 88°$; $c \wedge \gamma = 16°$; $\alpha = 1.666$; $\beta = 1.682$; $\gamma = 1.704$.

CONCLUSIONS

It is concluded that the "banded ironstone" of the Kangari Hills has been formed in sedimentary environment but characterized by ample introduction of acid volcanic elements. The main introduction of iron is ascribed to the volcanic exhalations, but the concentration of iron into narrow bands and strips to metamorphic differentiation.

GEOL. SURVEY DEPARTMENT,
NEW ENGLAND, FREETOWN, SIERRA LEONE,
June 25, 1956

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THE HARDNESS OF METALLIC MINERALS IN POLISHED SECTIONS

F. M. NAKHLA

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ABSTRACT

The first part of this paper deals with the application of a new microhardness tester, called Durimet, manufactured by E. Leitz, Ltd., Wetzlar, for determining Vickers hardness by making four-sided diamond shaped pyramidal indentation in the polished mineral surface. The length of the resulting diagonal is precisely measured by means of a measuring ocular.

The general construction of the apparatus, and the working procedure are briefly described. Results obtained from testing the polished surfaces of about fifty different mineral species, and the correlation of the results obtained with Talmage's Scale of Hardness are given in detail. The "Durimet" seems to be of valuable aid in helping to determine metallic opaque minerals, from their polished surfaces, particularly in small inclusions or discrete grains too small to be examined by Talmage's method. Furthermore, the instrument can also be used for determining Knoop hardness as well as scratch hardness simply by changing the diamond that produces the indentation.

The second part of the paper shows relationships between hardness and the textures encountered in the study of polished mineral surfaces. Among the most important relationships are the following:

(1) Ore minerals of the metallic elements belonging to the same group in Mendeleeff's Periodic Table are generally of the same class of hardness.

(2) Ex-solution textures, graphic intergrowths, and graphic replacement textures are generally shown by minerals belonging to the same grade of hardness.

(3) Soft minerals commonly replace hard ones, whereas minerals of the same hardness commonly replace each other. Rarely hard minerals replace softer minerals.

(4) In most ores the harder minerals seem to have crystallized earlier than the softer ones.

PART I

INTRODUCTION

ONE of the common methods used in the identification of metallic opaque minerals, from their polished surfaces, is the determination of their hardness. Talmage's hardness (1) is determined by producing a standard scratch, in the polished surface, under the microscope, by means of a particular apparatus. By knowing the position of a special sliding weight, on a graduated beam, the amount of pressure necessary to produce the standard scratch can be determined. Talmage divided opaque minerals into seven classes of hardness designated by the alphabetical letters A, B, C, D, E, F, and G. According to Talmage's Scale of Hardness the softest minerals fall under the class (A), and the hardest minerals fall under the class (G). Since Talmage's method for hardness determination, in polished sections, necessitates an elaborate equipment, and its application is limited only to the use of low power objective, it is practically impossible to make hardness determination on small mineral inclusions or grains that could be observed only by means of high power objectives. Furthermore, the time required to make a reliable hardness test averages about 15 minutes (2).

It is known that Vickers micro-hardness is determined by producing an indentation, in the surface of the substance, by means of a pyramid-shaped diamond and optically measuring the diagonal of the indentation. The Vickers diamond has a quadratic base. The apex angle between the opposed surfaces is 136°, while the depth of penetration equals one seventh (1/7) of the indentation diagonal. By knowing the test load applied (t) in grams, and the mean value of indentation diagonal in 0.001 mm., Vickers hardness can be determined from the following equation:

$$\text{HV (kg/mm}^2\text{)} = \frac{1854.4 \times t}{d^2}.$$

Identical to Vickers hardness is the Knoop hardness test. The Knoop pyramid diamond has a rhombic base surface. The longitudinal transverse diagonals of their surface are 7:1, and the depth of penetration is only about one thirtieth (1/30) of the longitudinal diagonal. The angles between the opposed pairs of edges are 172° and 130°, respectively. By knowing the test load applied (t) in grams, and the length of the longer diagonal (l) in 0.001 mm Knoop hardness will be:

$$\text{HK (kg/mm}^2\text{)} = \frac{14{,}230 \times t}{l^2}.$$

TABLE 1

MINERALS BELONGING TO CLASS (A) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Bismuth (native), Bi	m	64	86	132.5	230	
	HV	11.3	12.5	10.5	7	
Argentite, Ag_2S	m	24.5	33	46	66	78
	HV	77.2	85.1	87.6	85	91.4

m = length of Vickers diagonal in microns.
HV = Vickers hardness in kg/mm².

$$HV = \frac{1854.4 \times l}{d^2}.$$

l = weight in grams.
d = length of the diagonal in microns. (One micron = .001 mm.)

TABLE 2

MINERALS BELONGING TO CLASS (B) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Gold, Au	m	28.75	41.75	59	90	110
	HV	56.3	53.2	53.3	45.8	46
Antimony, Sb	m	26	38	55	80	100
	HV	68.6	64.2	61.3	57.9	55.6
Chalcocite, Cu_2S	m	24	37.5	53	76	91
	HV	80.5	65.9	66	64.2	67.2
Silver, Ag	m	17.5	26.25	38	68.5	90
	HV	151	134.5	128	79	68.7
Galena, PbS	m	22.5	33	50	68.5	89.5
	HV	91.6	85.1	74.2	79	69.5
Jamesonite, $Pb_4FeSb_6S_{14}$	m	17.25	26	39.75	65.25	81
	HV	156	137	118	87	84.8
Bornite, Cu_4FeS_4	m	19.75	30	42.5	60.5	75
	HV	118.5	103	103	101	98.9
Bismuthinite, Bi_2S_3	m	18	26	37.5	56	74
	HV	143	137	132	118	102
Covellite, CuS	m	18.6	26	39	58	71
	HV	134	137	122	110	110
Antimonite, Sb_2S_3	m	19.5	27	41	67	76
	HV	122	127	110	82.6	96.3
Antimonite, Sb_2S_3, another crystal orientation	m	17.5	25	35	53	63
	HV	151	148	151	132	140
Copper, Cu	m	15.2	20	30.2	36.5	46.5
	HV	201	232	203	278	257

The writer has determined the Vickers hardness of about fifty different mineral species, from their polished surfaces, by applying various testing loads ranging from 25 to 300 grams, by means of the relatively new, small, micro-hardness tester, called Durimet, manufactured by E. Leitz, Ltd., Wetzlar. A detailed description of the apparatus, and the techniques for using it are given in the Leitz Catalogues.

TABLE 3

MINERALS BELONGING TO CLASS (C) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Pyrargyrite, $Ag_6Sb_2S_4$	m	20	31	40.5	58	78
	HV	116	96.5	113	110	91.4
Proustite, $Ag_6As_2S_4$	m	18	27.75	41	58	78.5
	HV	143	121	110	110	90.4
Violarite, $(Ni, Fe)_2S_4$	m	15	23	33.25	47.5	61.5
	HV	206	175	167.5	164	148
Alabandite, MnS	m	15	22.5	32.5	46	61
	HV	206	183	176	175	150
Dyscrasite, Ag_3Sb	m	15	26.75	34	47	58.75
	HV	206	130	160	168	161
Arsenic, As	m	14	20	31.75	46.75	57.8
	HV	237	232	184	170	167
Bournonite, $Cu_2Pb_2Sb_2S_6$	m	13	19.25	31.25	46.25	56.8
	HV	274	250	190	174	172
Sphalerite, ZnS	m	14.5	20.75	30	45	55.5
	HV	220	215	206	183	180.5
Chalcopyrite, $CuFeS_2$	m	13.75	20.5	30.2	41	52.5
	HV	245	221	203	221	202

ADVANTAGES OF THE DURIMET

Some of the advantages of the "Durimet" are the following:

(1) It uses a testing load ranging from 15 to 500 grams.
(2) Exchangeable diamonds from Vickers to Knoop test and for scratch hardness testing.
(3) Variable magnifications; mineral inclusions and grains about 0.02 mm in diameter can be easily tested.
(4) The indentation can be directly read with a precision of .0005 mm, while the relative measuring accuracy equals .0002 mm.
(5) Vibrationless working cycle of hardness test mechanism.
(6) Slippage compensation of indenting body.

(7) Time required to make a reliable test is about 15 seconds.
(8) The instrument can be used for testing small inclusions of mineral aggregates in polished sections, as well as, of thin layers, such as foil materials, varnishes, plastics, edges and points of turning, milling, and other cutting tools, etc. . . .

RESULTS

Tables from 1 to 7 summarize the Vickers hardness values made on the polished surfaces of about fifty different mineral species, using testing loads

TABLE 4

MINERALS BELONGING TO CLASS (D) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Stannite, Cu_2FeSnS_4	*m*	14.5	21.25	31.5	41.25	57
	HV	220	205	187	217.5	171
Pyrrhotite, Fe_nS_{n+1}	*m*	12.25	17.5	25.5	38.75	47
	HV	308.5	303	285	247	252
Enargite, $Cu_4As_2S_6$	*m*	10	15.75	23.5	35	45.5
	HV	464	373.5	336	303	269
Pentlandite, (Fe, Ni)S	*m*	12	17	24.5	36	44.5
	HV	322	321	309	286	281
Tetrahedrite, $Cu_{12}Fe_2Sb_4S_{13}$	*m*	10	15.5	24.5	35	43
	HV	464	386	309	303	301
Tennantite, $Cu_{12}Fe_2As_4S_{13}$	*m*	9.75	14	20.5	31.25	40.2
	HV	488	473	441	380	344
Freibergite, $Cu_{12}Ag_{10}Fe_2Sb_4S_{13}$	*m*	10.2	14.75	22	30.5	40
	HV	446	426	383	399	348
Hausmannite, Mn_3O_4	*m*	8.5	12.5	18.5	27	33.5
	HV	642	593	542	509	495.5
Psilomelane, MnO_2, BaO, H_2O	*m*	6	10	15.5	22	27
	HV	1,288	927	772	766	763

of 25, 50, 100, 200, and 300 grams, respectively. The polished mineral surfaces examined are standard specimens of already identified minerals, and were prepared by both hand and mechanical polishing processes. Each table includes a certain number of minerals that belong to the same class of hardness in Talmage's Scale. Vickers hardness (HV) is determined either from Vickers Conversion Tables, or from the following equation:

$$\text{HV (kg/mm}^2) = \frac{1854.4 \times t}{d^2},$$

TABLE 5

MINERALS BELONGING TO CLASS (E) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Millerite, NiS	*m*	11	18.25	26	37.5	46
	HV	383	278.5	274	264	263
Wolframite, (Fe, Mn)WO_4	*m*	8.5	13.5	19.5	30	36.75
	HV	642	509	488	412	411
Ullmannite, NiSbS	*m*	7	12.5	18.5	27.05	34.5
	HV	946	593	542	507	467.5
Niccolite, $NiAs_2$	*m*	8.5	13.75	17	27.5	34
	HV	642	490	642	490	481
Manganite, Mn_2O_3	*m*	7	12.5	18.25	27.75	32.25
	HV	946	593	557	481.5	537
Goethite, FeO(OH)	*m*	6	11.5	18	25	30.75
	HV	1,288	701	572	593	588
Rammelsbergite, $NiAs_2$	*m*	7	10.5	15.5	22	29
	HV	946	841	772	766	662

TABLE 6

MINERALS BELONGING TO CLASS (F) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Chloanthite-smaltite, $(Ni, Co)As_2$	*m*	8	11.5	16.5	26	32
	HV	724	701	681	549	543
Magnetite, Fe_3O_4	*m*	7	10	14.5	22.25	29
	HV	946	927	882	749.5	662
Nickeliferous loellingite, $(Fe, Ni)As_2$	*m*	8.2	11	16.5	23	28.2
	HV	689	766	681	701	700
Loellingite, $FeAs_2$	*m*	7.5	10	15.5	22	26.5
	HV	724	927	772	766	792
Gersdorffite, NiAsS	*m*	6.5	9.5	14	20	26.5
	HV	1,097	1,027	946	927	792
Safflorite-loellingite, $(Co, Fe)As_2$	*m*	6.25	9.75	14.2	19.5	26.5
	HV	1,188	975	920	975	792
Arsenopyrite, FeAsS	*m*	5.5	8.5	13.5	19.5	25
	HV	1,533	1,283	1,018	975	890
Pyrite, FeS_2	*m*	3.75	6.5	9.5	15.5	18.5
	HV	3,296	2,194	2,054	1,543	1,625

where (l) is the testing load applied in grams, and (d) is the length of the diagonal in microns (one micron = 0.001 mm). For example, if the weight applied is 50 grams, and the length of the diagonal is 33 microns, then Vickers hardness (HV) can be calculated as follows:

$$\text{HV (kg/mm}^2) = \frac{1854.4 \times 50}{(33)^2} = 85.1.$$

The data obtained are graphically represented in Figures 1 to 4. Figures 1, and 2 show the relation between the length of the diagonals of Vickers indentations, measured in microns, and the various testing loads applied in

TABLE 7

MINERALS BELONGING TO CLASS (G) IN TALMAGE'S SCALE

Minerals		Weights applied in grams				
		25	50	100	200	300
Braunite, Mn_7SiO_{12}	m	6.25	10	15.5	22	29
	HV	1,188	927	772	766	662
Ilmenite, $FeTiO_3$	m	6.5	9.5	13.5	19.5	26
	HV	1,097	1,027	1,018	975	823
Cobaltite, CoAsS	m	4.75	8.5	12.25	18.5	21.5
	HV	2,055	1,283	1,215	1,082	1,204
Cassiterite, SnO_2	m	4.5	8.25	11.25	17.75	21.85
	HV	2,290	1,363	1,464	1,174	1,162
Chromite, $FeCr_2O_4$	m	4.5	7.5	10.25	14.75	19
	HV	2,290	1,648	1,765	1,704	1,541

grams. Figure 3 illustrates the relation between Vickers hardness (kg/mm^2) of certain minerals in relation to the test load. Figure 4 shows the Vickers indentations made on different mineral species with variable testing loads.

DISCUSSION OF RESULTS

Vickers hardness test has been widely used in the examination of various types of steel, alloys, foil material, as well as, edges and points of turning, milling, and other cutting tools, because it embraces the whole technical hardness range, and excels all other methods in accuracy. Recently, the author has applied it for hardness determination of polished metallic mineral surfaces. The determination of micro-hardness by means of the new Durimet seems to be of valuable aid in the identification of an unknown mineral species. Vickers hardness determination of polished mineral surfaces, should not be regarded as a panacea in the identification of opaque minerals. It is simply an additional technique at the disposal of the mineralogist, to be used together with other optical and chemical methods of mineral investigation.

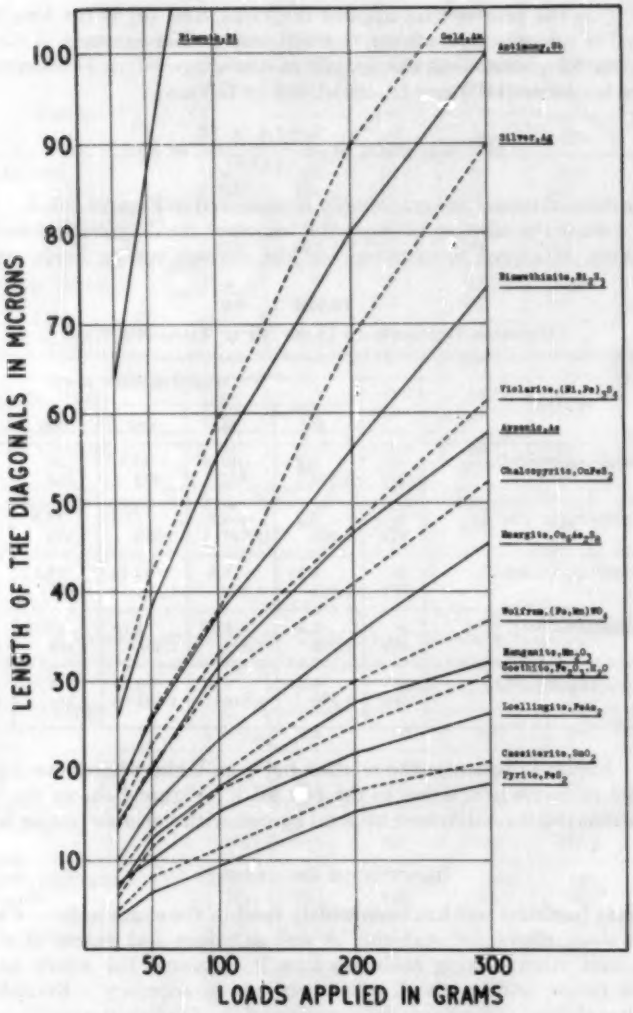


FIG. 1.

Vickers hardness tests were made only on the common, and some of the rare, mineral species that were available to the author. Therefore, it was not possible to establish a new hardness scale, analogous to Talmage's Scale of Hardness, owing to the lack of sufficient data. The main object of the first part of this paper is to show the application of micro-hardness tech-

nique, in the study of polished mineral surfaces, as an aid in their determination particularly in minute inclusions, and discrete small grains.

Some discrepencies between Vickers hardness values and Talmage's Scale of hardness may be mentioned as follows:

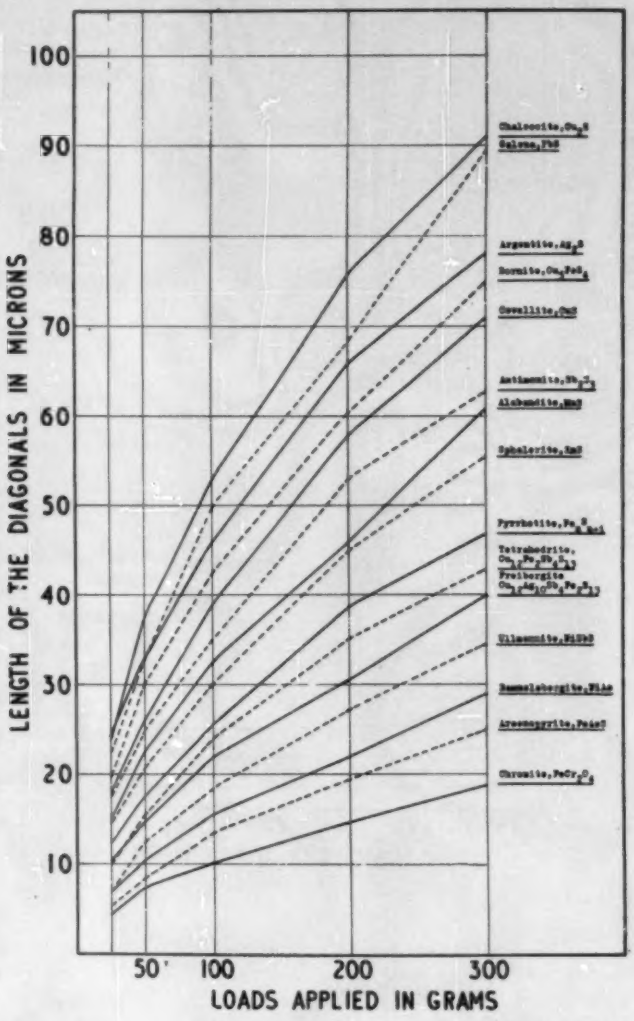


FIG. 2.

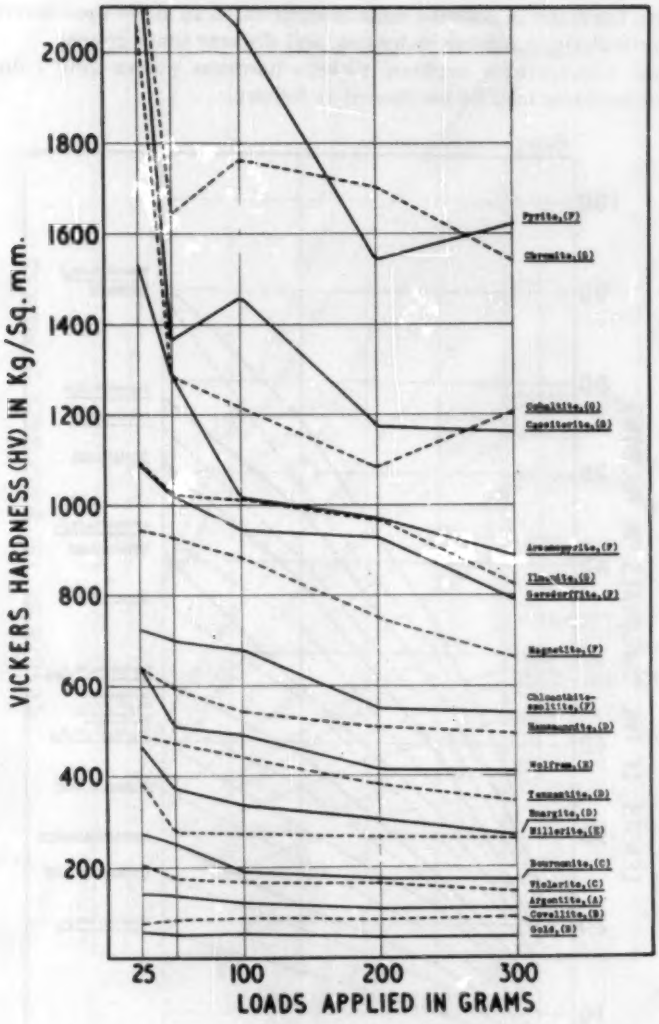
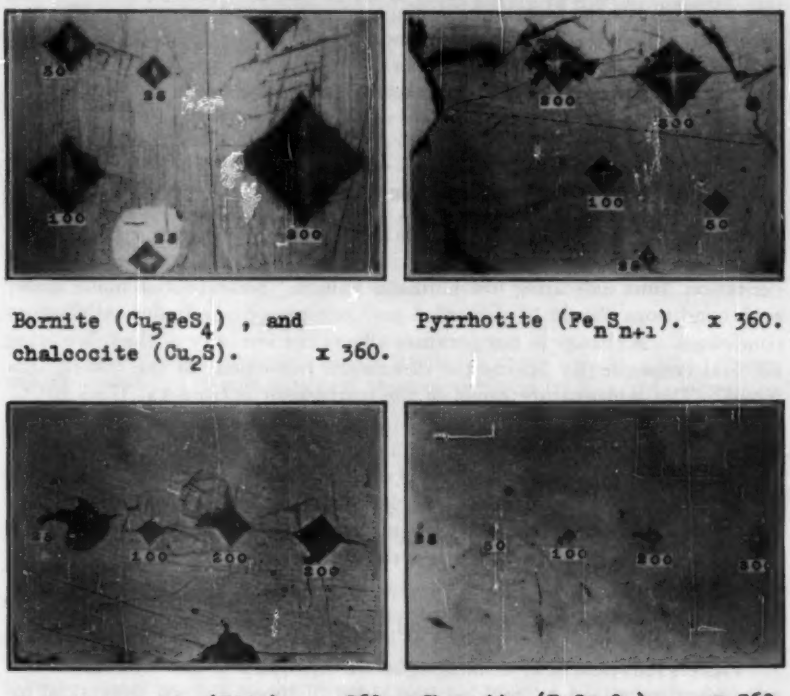


FIG. 3.

(1) According to Vickers hardness test native gold, antimony, silver, chalcocite, and galena are softer than argentite. In Talmage's Scale argentite belongs to class (A) whereas the other minerals belong to class (B).

(2) Hausmannite, and some varieties of psilomelane, which belong to class (D) in Talmage's Scale, are in fact harder than the majority of the minerals belonging to class (E), of which millerite and wolframite are examples.
(3) Vickers hardness tests proved that pyrite is harder than ilmenite, but according to Talmage pyrite is a member of class (F), and ilmenite of class (G).

VICKERS INDENTATIONS MADE on DIFFERENT MINERAL SPECIES WITH VARIABLE TESTING WEIGHTS



Bornite (Cu_5FeS_4) , and chalcocite (Cu_2S). x 360.

Pyrrhotite (Fe_nS_{n+1}). x 360.

Rammelsbergite ($NiAs_2$). x 360. Chromite ($FeCr_2O_4$). x 360.

FIG. 4.

These discrepancies may be attributed to the accuracy of Vickers hardness tests, and to the difference in the nature of the two techniques.

It was also noticed that Vickers hardness tests, for most of the common minerals, are of diagnostic value on applying loads ranging from 200 to 300 grams. Furthermore, on applying small testing weights the hardness values

do not vary considerably in different crystallographic directions; but the variation increases on applying testing loads greater than 50 grams. This phenomenon was clearly observed in fibrous or acicular minerals such as, antimonite, bismuthinite, and jamesonite. Hard minerals, like pyrite and rammelsbergite, produced large, shell-shaped cracks on applying loads of 100, 200, and 300 grams, while fine cracks resulted from small loads of 25, and 50 grams.

Mechanical polishing has a small effect upon surface hardness. Regardless of the method of polishing, Vickers hardness can be correctly determined if the thickness of the mineral, or any material examined, is at least $1\frac{1}{2}$ times as great as the length of the diagonal of the indentation, i.e., 10 times the depth of penetration of the Vickers diamond. The depth of penetration depends upon the nature of the mineral, and the load applied.

When using the "Durimet" the following conditions should be fulfilled:

(1) A vibrationless working room.
(2) A room temperature of about 25° C.
(3) Clean working room, free from dust, vapor, and acids.

If during the time when an indentation is being made, the instrument is subjected to an unanticipated vibration, this will result in an enlarged indentation, thus indicating low hardness values. Indentations made under such conditions should be discarded and new ones made under satisfactory conditions. A change in temperature affects the viscosity of the lubricating oil, and consequently affects the downward movement of the testing diamond. The temperature range of the instrument is from 15° C to 30° C. Lower or higher temperatures necessitates the use of suitable oil, and recalibration of the instrument. The diamond may become dirty in coming in contact with dirty specimens, or if the working room is unclean. Should this occur, it may be cleaned with a soft cloth and, if necessary, with light fluid. If the hardness tests are carried out under the above conditions, reproducible values are possible, and the test results obtained by different observers are in closer agreement.

CONCLUSION

Vickers hardness of metallic opaque minerals, in polished sections, can be precisely determined by making four-sided diamond shaped pyramidal indentation, using different testing loads, by means of a special micro-hardness tester called "Durimet." The technique seems to be of valuable aid in the identification of opaque minerals particularly in grains and minute inclusions too small to be observed by the low power objective under the microscope. The results of the tests are reproducible, and more reliable than any other technique for the hardness determination of polished opaque mineral surfaces. Further work is needed in order to establish a new scale of hardness for practical use in the examination of opaque minerals.

PART II

INTRODUCTION

The explanation of the tendency that certain minerals form ex-solution textures, graphic intergrowths, as well as, the selectivity of replacement are not thoroughly understood. The chief governing factors are, the internal space-lattice structure of the minerals, nature of the chemical bonds operating between the various atoms or ions, relative solubility, and stability. A. B. Edwards (3), in 1947, gave an excellent survey of the textures of ore minerals and their significance in the determination of the paragenesis, and in solving ore-dressing problems.

In the following sections it will be shown that:

(1) The majority of metallic opaque minerals are soft.
(2) Oxides, sulfides, and sulfosalts that form ex-solution textures, due to unmixing of solid solutions on cooling, are shown by minerals of the same grade of hardness.
(3) Soft minerals commonly replace harder ones, and minerals of the same hardness commonly replace each other.
(4) The nature of the element may be one of the factors that determine the hardness of its metallic ore minerals.

TALMAGE'S SCALE OF HARDNESS

For convenience, minerals falling under Talmage's A, B, and C classes will be considered as soft minerals, those designated by F, and G letters are regarded as hard minerals, and those belonging to D, and E groups as minerals of medium hardness. According to this general classification of the relative hardness of ore minerals, in polished sections, the following facts emerge:

(1) About 63 percent of the ore minerals are soft; nearly 22 percent are minerals of medium hardness, and the rest (about 15 percent) are hard minerals.

(2) More than 70 percent of the opaque minerals of Sb, Bi, Cu, Au, Pb, Hg, Sn, Ag, Se, and Te are soft minerals. On the contrary, less than 25 percent of the opaque minerals of Mn, Fe, Co, and Ni are soft. Elements whose recorded opaque minerals are less than seven in number were not taken in consideration in the above statistical results. This fact led to the conclusion that the elements belonging to the same group in Mendeleeff's Periodic Table also show great similarity in the hardness of their metallic minerals. For example, most of the opaque minerals of the group Cu, Ag, and Au are soft; the majority of As, Sb, and Bi minerals are also soft. On the contrary, most of the ore minerals of the transitional elements group, of which Fe, Co, and Ni are examples, are either of high or medium hardness.

It is also important to mention that the percentage of the soft minerals increases as the atomic number or atomic radius of the elements, belonging to the same group, becomes greater, as shown in Table 8.

TABLE 8

RELATIONSHIP BETWEEN ATOMIC RADIUS AND PERCENTAGE OF SOFT MINERALS

Elements	Atomic number	Atomic radius	% of soft minerals	% of hard minerals
Cu	29	1.276	74	26
Ag	47	1.442	97	3
Au	79	1.439	100	—
As	33	1.16	53	47
Sb	51	1.614	77	23
Bi	83	1.82	94	6
Sn	50	1.582	71	29
Pb	82	1.747	98	2
Zn	30	1.374	33.3	66.7
Hg	80	1.55	109	—
Fe	26	1.27	22	78
Co	27	1.257	—	100
Ni	28	1.244	11	89

This does not apply to the minerals of the transitional elements group, the metallic ore minerals of which are mainly of medium and high degrees of hardness. Since the hardness of a mineral is a function of its internal space-lattice structure, it is most probable that as the atomic radius of the element becomes bigger the forces between the various atoms or ions will be inversely proportional to the square root of the distance between the atoms or ions, thus producing an increase in the softness of the corresponding mineral.

TABLE 9

MINERALS FORMING EX-SOLUTION TEXTURES

Soft minerals	Minerals of medium hardness	Hard minerals
Bismuthinite-argentite		Cassiterite-tantalite
Bismuthinite-emplectite	Tetrahedrite-tennantite	Chromite-hematite
Bornite-chalcocite		Chromite-ilmenite
Bornite-chalcopyrite		Corudum-hematite
Bornite-klaprothite	Famatinite-enargite	Hematite-rutile
Bornite-tetrahedrite		Hematite-ilmenite
Bournonite-seligmannite		Hematite-ilmenite-rutile
Chalcocite-coveilite	Linnaeite-millerite	Ilmenite-pyrophanite
Chalcocite-stromeyrite		Ilmenite-hematite
Chalcopyrite-cubanite		Jacobsite-hausmannite
Chalcopyrite-sphalerite	Pyrrhotite-pentlandite	Magnetite-hematite
Chalcostibite-emplectite		Magnetite-ilmenite
Cosalite-dufrenoysite		Magnetite-pyrophanite
Galena-argentite	Stannite-chalcopyrite	Magnetite-rutile
Galena-galenobismutite		Magnetite-spinnel
Galena-proustite		Manganosite-zincite
Galena-pyrargyrite	Stannite-tetrahedrite	Tantalite-columbite
Miargyrite-matildite		Tantalite-rutile
Miargyrite-aramayoite		Tantalite-ilmenite
Pyrargyrite-proustite		
Silver-dyscrasite		
Zinkenite-galenobismutite		

HARDNESS AND ITS RELATION TO THE TEXTURES OF ORE MINERALS

Ex-solution Textures—Table 9 shows the minerals that enter in the formation of solid solutions, and produce ex-solution textures due to unmixing on cooling. Host or solvent mineral is named first; the temperature of unmixing varies between 450° C for chalcopyrite and cubanite, and 75° C for chalcocite and covellite. References for this table are found in Edward's book (3, p. 73).

The ex-solution textures of the above minerals are evidently shown by mineral pairs that can form isomorphous series in which the internal space-lattice structure is generally the same so that the substitution of one element by another will not produce an appreciable distortion in the internal structure of the mineral.

Metasomatic Replacement.—The study of polished mineral surfaces of metallic ore minerals, from different localities, shows that hard minerals are commonly replaced by softer minerals. The following examples have been recorded by different authors:

Gold	(B)[1]	replaces	pyrite	(F)
Gold	(B)	replaces	arsenopyrite	(F)
Chalcocite	(B)	replaces	klaprothite	(C)
Cha cocite	(B)	replaces	pyrite	(F)
Chalcocite	(B)	replaces	bornite	(B)
Covellite	(B)	replaces	chalcopyrite	(C)
Galena	(B)	replaces	pyrite	(F)
Galena	(B)	replaces	sphalerite	(C)
Galena	(B)	replaces	tetrahedrite	(D)
Ricardite	(B)	replaces	krennerite	(C)
Silver	(B)	replaces	niccolite	(E)
Silver	(B)	replaces	cobaltite	(G)
Silver	(B)	replaces	marcasite	(E)
Chalcopyrite	(C)	replaces	niccolite	(E)
Chalcopyrite	(C)	replaces	tennantite	(D)
Chalcopyrite	(C)	replaces	pyrite	(F)
Sphalerite	(C)	replaces	pyrite	(F)
Psilomelane	(D)	replaces	jacobsite	(G)
Stannite	(D)	replaces	cassiterite	(G)
Goethite	(E)	replaces	pyrite	(F)
Limonite	(E)	replaces	pyrite	(F)

[1] Letters refer to the class of the mineral hardness in Talmage's Scale.

Also, minerals of the same grade of hardness commonly replace each other as shown by the following examples:

Chalcopyrite	(C)	replaces	sphalerite	(C)
Covellite	(B)	replaces	bornite	(B)
Covellite	(B)	replaces	galena	(B)
Stromeyrite	(B)	replaces	galena	(B)
Anglesite	(B)	replaces	galena	(B)
Galena	(B)	replaces	bornite	(B)
Silver	(B)	replaces	bornite	(B)
Arsenopyrite	(F)	replaces	loellingite	(F)
Martite	(G)	replaces	magnetite	(F)
Rutile	(G)	replaces	ilmenite	(G)
Hematite	(G)	replaces	ilmenite	(G)

(3) *Selective Replacement.*—Some minerals when replacing a complex ore show preference towards the replacement of particular mineral species. For example, chalcocite (B) when invading a complex ore containing pyrite (F), and chalcopyrite (C) selectively replaces chalcopyrite, which is softer than pyrite. Covellite (B) tends to replace bornite (B) in preference to either chalcopyrite (C), or pyrite (F). A third example is the replacement of bornite (B) by chalcocite (B) in a mixture of bornite (B) and klaprothite (C). Similarly, galena (B) tends to replace sphalerite (C) in preference to either tetrahedrite (D), or pyrite (F). It is evident that the selectivity of replacement is, generally, directed towards the softer minerals in preference to the harder ones. However, it must be understood that other factors such as, the temperature of formation, crystallographic orientation, similarity in composition, stability, and relative solubility play an important role in determining the selectivity of replacement.

(4) *Graphic Replacement Textures*: These replacement textures are generally found in relatively soft minerals with hardness less than (D) in Talmage's Scale. A list of the minerals showing graphic replacement textures can be found in Edward's book, page 105. Most of the mineral pairs forming these textures possess the same degree of hardness.

(5) *Hardness and the Sequence of Ore Minerals*: Gilbert (4), in 1924, pointed out that in most ores the harder minerals appear to have crystallized earlier than the softer minerals. He suggested that there are relations between hardness and solubility, as well as, between hardness and rarity of the elements.

CONCLUSION

It is obvious that there is a relationship between the atomic radii of the metallic elements and the hardness of their metallic opaque minerals which, furthermore, depends also upon the type of the internal space-lattice structure. It must be remembered that Talmage's hardness means resistance against abrasion, and is therefore a two dimensional property, while Mohs hardness is only measured in one direction, and is therefore a vectorial property that varies according to the orientation of the mineral.

Further work is required taking in consideration the type of space-lattice structure, degree of ionization, and the co-ordination numbers of the different elements. This may probably lead to the establishment of an, at least, semi-quantitative formula showing the relation between hardness and these various factors. If such a relation exists one may be able to predict the hardness of any mineral by applying such equation. The values of Vickers and Knoop hardness tests may be of valuable aid in confirming the validity of such equation.

As regards the selectivity of replacement it is clear that, for example, in the case of chalcocite replacing chalcopyrite instead of pyrite, the pyrite is earlier than the chalcopyrite because it has a higher temperature of formation. If the temperature of formation is the sole determining factor in selective replacement, pyrite should be replaced easier than chalcopyrite, being less stable at lower temperatures, which is evidently not the case. The

fact that soft minerals, generally, replace harder ones is merely based on the assumption that hard minerals are formed in an earlier stage at higher temperatures, while soft minerals crystallize in a later stage at lower temperatures. Naturally, the later soft minerals will replace the earlier hard minerals. On the other hand, the selectivity of replacement is governed by other factors, such as looser packing, greater solubility, substitution of atoms or ions by other elements possessing the same atomic radius, etc. . . . The selectivity of replacement seems to depend upon several factors that must be considered separately for each case.

MINING GEOLOGY DEPT.,
CAIRO UNIVERSITY,
CAIRO, EGYPT,
Aug. 15, 1956

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DISCUSSIONS

GEOCHEMISTRY OF SPHALERITE FROM THE STAR MINE, COEUR D'ALENE DISTRICT, IDAHO

Sir: Application of the sphalerite geothermometer (Kullerud, 1953) has been criticized in a paper of the above title by Verne C. Fryklund, Jr., and Janet D. Fletcher. This publication appeared in ECONOMIC GEOLOGY, volume 51, number 3, pp. 223–247, 1956. The sphalerite geothermometer is based on the ability of iron to substitute for zinc in zinc-sulfide as a function of temperature and pressure.

The authors state (p. 230): "Kullerud has made the tacit assumption that the shape and position of this solid solvus curve would not be greatly affected by the presence of minor constituents. The writers are willing to make the same assumption, but would like to point out that the literature of metallography is replete with examples of binary systems whose solid-state fields can be drastically altered by small amounts of a third component, but perhaps not in the minute quantities common to many minor elements."

Experiments designed to determine the influence of manganese and cadmium on the solubility of Fe in ZnS have been described on pp. 112–119 in my paper on the FeS—ZnS system. These studies showed that up to 2 percent of Mn and/or Cd had no measurable influence on the solubility of iron in sphalerite. In other words, the iron content of a sphalerite is not *measurably* influenced by the presence of cadmium or manganese as long as the latter elements do not exceed 2 mol percent. It is well known that, next to iron, manganese and cadmium are the most common minor constituents in sphalerites. Other elements such as Ga, Ge, Hg, In, etc., may likewise substitute for zinc in sphalerite; however, the sum of these elements will only very rarely amount to more than 0.01 percent. It was assumed in my publication (Kullerud, 1953) that a total of 0.01 percent of a number of trace elements would not change the FeS—ZnS solvus curve measurably. Such a conclusion is logical because these trace elements play the same role as Mn and Cd by replacing zinc, but are hundreds of times less abundant.

Experiments have shown that 6.0 mol percent MnS lowers the α-β inversion temperature of ZnS by about 200° C and that 6.0 mol percent CdS depresses the inversion temperature by about 300° C. From these data it is deduced that 0.01 mol percent of either MnS or CdS will depress the inversion temperature by about 0.5° C. Since Ga, Ge, Hg, In, etc., behave like Mn and Cd by replacing Zn, the inversion point depression caused by a sum total of 0.01 percent of such trace elements would be of the order of magnitude of 0.5° C, which, of course, is of no consequence.

Fryklund and Fletcher further write on p. 230: "Even if it could be satisfactorily demonstrated that a naturally occurring sphalerite formed in an environment where there was an excess of Fe, it seems doubtful that the temperatures of formation deduced from study of the artificial system FeS—ZnS can be applied to sphalerite from an ore deposit. A major difficulty in using the Fe content of the sphalerite to indicate the precise temperature of formation is that no information is available on the system FeS—ZnS—H_2O. Water was surely a major component of the ore-forming solutions. Judging from its behavior in other systems, the presence of water is likely to have a considerable effect on the FeS—ZnS solvus line. The temperatures determined from Kullerud's data may therefore not give an absolute scale to apply to an ore deposit."

The role of water and other volatiles (CO_2, etc.) is generally misunderstood when sub-solidus conditions are under discussion.

In the case of hydrous mineral reactions, the presence of water is essential to the composition of the products. The situation is quite different in systems where water does not enter into the reacting phases. In sulfide systems the presence of volatiles such as water will influence the melting relations in cases where water can form a homogeneous melt with the sulfides. On the other hand, water (or CO_2) cannot influence the sub-solidus relations (mix-crystal composition, inversion points, etc.) where it does not enter into the phases. It is for this reason that one is able to use sub-solidus phase relations as geothermometers (e.g., sphalerite-pyrrhotite mix-crystal composition) where the presence of non-participating volatiles is immaterial. Volatiles such as selenium and tellurium, however, may replace sulfur and, therefore, can influence the sub-solidus relations. However, the S:Se ratio in sphalerites is normally exceeding 10,000 to 1 and the S:Te ratio is considerably larger. For this reason both selenium and tellurium have negligible influence on the sub-solidus relations.

Finally, on page 246, in their conclusions, Fryklund and Fletcher state: "4. The minor elements in sphalerite, other than Mn (Fe should be considered a major element), cannot be indicators of formation temperature because equilibrium concentrations are rarely, if ever, obtained. This conclusion should have been reached on theoretical grounds before the writers started the work. The writers suspect this conclusion applies to most minerals."

The manganese content in sphalerite cannot be used as a geological thermometer for the Star Mine ores because MnS is not present. If mix-crystals of the type (Mn, Zn)S are to be used for geological thermometry, the presence of free MnS is required to insure that the mix-crystals were saturated on manganese under the prevailing pressure and temperature conditions of ore formation. However, it is likely that minor elements such as manganese and cadmium may be used in geological thermometry, if their relative abundance as a function of temperature is studied in coexisting minerals. (See for instance H. P. Eugster in Annual Report of the Director of the Geophysical Laboratory, Carnegie Inst. of Wash. Year Book No. 54, pp. 112–114, 1955.) Thus in simultaneously deposited pyrrhotite and sphalerite the ratio between manganese concentration in pyrrhotite and that in sphalerite should be a func-

tion of the temperature, pressure conditions prevailing during the formation of the mineral assemblage.

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CARNEGIE INSTITUTION OF WASHINGTON,
WASHINGTON, D. C.,
July 28, 1956

REFERENCE

Kullerud, Gunnar, 1953, The FeS—ZnS system: a geological thermometer: Norsk Geologisk Tidsskrift, v. 32, p. 61–147.

IS LEUCOXENE ALWAYS FINELY CRYSTALLINE RUTILE?

Sir: In a recent paper published in this Journal (4) three stages in the alteration of ilmenite in beach sands are discussed. In Stage 1 (*Patchy ilmenite*) patchy intergrowths of altered and unaltered ilmenite are recognized. In Stage 2 (*Amorphous iron-titanium oxide*) the product is essentially amorphous and is designated amorphous iron-titanium oxide. It is gray, opaque, and shows no internal reflections, but some grains show a weak anisotropism. In Stage 3 (*Leucoxene*) the final stage of alteration is leucoxene that is finely crystalline. However, in many grains the first and third stages overlap. X-ray patterns of grains belonging to Stage 2 gave only a few extremely diffuse spots that could not be identified and were interpreted as a pattern very close to that of the amorphous state. Brown or white leucoxene belonging to Stage 3 gave X-ray patterns of rutile, except one which gave the pattern of brookite.

My experience with leucoxene began about 1934 during a study of the diaspore clays of Missouri. A concentrate of leucoxene analyzing 24 percent TiO_2 was isolated from high-grade diaspore clay. Leucoxene occurring as a coating on large rutile crystals from Virginia analyzed 57 percent TiO_2. Professor Paul F. Kerr reported that these samples gave no X-ray patterns (1). From 1939–46 leucoxene was collected (2) and isolated from several sources. W. F. Bradley, J. W. Gruner and J. M. Axelrod cooperated in the investigation by making X-ray patterns, and the U. S. Bureau of Standards by making electron micrographs. The laboratories of the U. S. Geological Survey and the Illinois State Geological Survey contributed chemical analyses of the samples separated by me.

Leucoxene with 41 percent TiO_2 was concentrated from a clay derived by the weathering of basaltic rocks of Hawaii (10). It gave the X-ray pattern of anatase.

Leucoxene with 74 percent TiO_2 occurs as a coating on ilmenite from Norway, and its X-ray pattern is similar to that of anatase. The CaO content of the leucoxene coating rutile from Virginia is 1.3 percent and in the leucoxene concentrated by the weathering of basaltic lavas of Hawaii the CaO is 0.17 percent. In contrast to these samples the leucoxene coating on ilmenite from Norway contains 5.8 percent CaO. If this CaO is combined with SiO_2 and TiO_2 in the ratio required to form sphene the resulting compound must be

present as a noncrystalline mineral because the X-ray pattern does not indicate the presence of any sphene.

Leucoxene associated with a clay from Andersonville, Georgia (3) gave the X-ray pattern of anatase. Optical and X-ray data indicate that kaolinite is represented in the chemical analysis of this concentrate.

Leucoxene from a small pocket-filling associated with ilmenite at Roseland, Virginia (3) gave an X-ray pattern of anatase, sphene, and apatite. A chemical analysis of this sample shows that 48.10 percent TiO_2, 12.81 percent P_2O_5, 17.44 percent CaO, 9.16 percent SiO_2, 2.72 percent Al_2O_3, 3.07 percent Fe_2O_3, 2.04 percent H_2O-, and 5.14 percent H_2O+ are present. After combining sufficient CaO with 12.81 percent P_2O_5 to form apatite, only 0.7 percent CaO is available to combine with SiO_2 and TiO_2 to form the sphene that is recorded in its X-ray pattern.

Samples of xanthitane and hydrotitanite were obtained from the U. S. National Museum, so that chemical analyses and X-ray patterns could be run on parts of the same specimen. The reanalysis of our specimen of xanthitane by R. E. Stevens (3) varies slightly from the original published by Eakins in 1888. It consists of a yellow birefringent mineral that occurs as wedge-shaped pseudomorphs that have been interpreted as indicating it is an alteration of sphene. It is of interest here because it gives an X-ray pattern of anatase and sphene and because it is considered by some writers as similar to leucoxene. Our sample, which gave the X-ray pattern of sphene, contains only 0.18 percent CaO, so that lines of sphene recorded in its X-ray pattern come from less than 1 percent sphene.

Hydrotitanite from Arkansas is opaque, grayish white by reflected light, and resembles leucoxene. It occurs as pseudomorphic crystals and is considered to be an altered form of perovskite or dysanalyte. The new analysis by Joseph J. Fahey (3) of pseudomorphic crystals furnished by the U. S. National Museum differs from the original published by Koenig in 1876 in that it contains 22.32 percent Al_2O_3 and 10.38 percent $(Cb, Ta)_2O_5$. Although sufficient CaO, SiO_2 and TiO_2 are recorded in this analysis to form as much sphene as that present in the xanthitane, it is not present in a form that is recorded in its X-ray pattern. This material shows that considerable impurities can be present in a sample having the optical properties of leucoxene and its X-ray pattern reveals only anatase. X-ray patterns made independently at Harvard University on other samples of xanthitane and hydrotitanite gave X-ray powder patterns identical with anatase patterns (8).

Because several specimens of leucoxene, such as the leucoxene coating ilmenite from Norway, gave X-ray patterns that are identical to those of natural and synthetic anatase, electron micrographs of each were obtained for comparison. Electron micrographs of synthetic anatase were obtained through the courtesy of RCA and showed pseudocubic crystals of the anatase. The U. S. Bureau of Standards prepared electron micrographs of leucoxene from the clay at the Ideal Mine, Andersonville, Georgia, and from the hydrotitanite from Arkansas, each of which gave X-ray patterns of anatase. The electron micrographs show that the material is formless or amorphous. A reasonable explanation of this observation is that the X-ray pattern of anatase obtained

from these samples comes from one percent or less of well-crystallized grains of anatase that are masked by the bulk of the leucoxene, which is amorphous.

Other investigators, including McCartney (7) and Coil (6), considered that leucoxene can be amorphous. Tyler and Marsden (9) recognized that the X-ray pattern of leucoxene is similar to that of rutile, anatase, and perhaps brookite. They concluded that leucoxene does not exist as a distinct mineral species, but it seems advisable to retain the name leucoxene to designate microcrystalline TiO_2. In 1949 (2) and in 1952 (3), I recommended that leucoxene should be retained as a petrographic term for the alteration product in which titania occurs in rocks. This is in keeping with the usage of the term proposed by Gumbel in 1874.

The answer to my question given as the title of this discussion is therefore, no, leucoxene is not always crystalline rutile. X-ray patterns of leucoxene are similar to those of anatase, sphene, brookite, as well as rutile. The lack of any X-ray pattern from some samples of leucoxene and the electron micrographs of some leucoxene samples submitted by me to the U. S. Bureau of Standards indicate that leucoxene is not always crystalline. Thus, the amorphous iron-titanium oxide of Stage 2 (4) can be considered as leucoxene, as it is an alteration product in which titania occurs in rocks. Furthermore, the chemical and mineralogical variability of leucoxene indicates it is not a definite mineral species, but is an alteration product in the same sense as clay. Sentences quoted from Bailey et al. (4) indicate they are aware of this variability. "Leucoxene has a variable character. . . . Actually, the microscope shows that brown leucoxene is not sharply distinct from either amorphous iron-titanium oxide on the one hand or white leucoxene on the other. The alteration of amorphous oxides to leucoxene proceeds on a minute scale. . . . No sharp line between brown and white leucoxene can be drawn, as various grains show internal reflections ranging from brown to white."

Since leucoxene is variable it seems advisable to avoid the impression that what applies to leucoxene at one locality also applies to leucoxene elsewhere. In the statement attributed to Cannon (4) "that leucoxene is microfine, crystalline rutile" the reader may be left with the impression that all leucoxene is microcrystalline rutile. Actually, Cannon's statement that "the pure leucoxene is a mass of microfine rutile crystals" was applied only to the samples from Trail Ridge, Florida, examined by him in 1950 (5).

My second question is: has the *amorphous iron-titanium oxide* of *Stage 2* a higher moisture or water content than that of the *leucoxene* of *Stage 3*? Coil (6) considered leucoxene in the Permian sandstones of Oklahoma to be amorphous hydrous titanium oxide. The chemical analyses of several samples of leucoxene concentrated by me show several percent of water present. Unfortunately each of these also contains some Al_2O_3 and Fe_2O_3 so that allotment of some of the water had to be made to minerals indicated to be present by X-ray and optical data on the samples. In several samples a slight excess of water remains after assigning the amount of water required for these molecules. The evidence is not conclusive as to whether the water in these specimens of leucoxene is combined as a hydrous titanium oxide or is absorbed on the smallest particles of an oxide of titanium that could conceivably ap-

proach colloidal dimensions. The answer to the question of the water in the material of *Stage 2* is complicated by the possibility that some water may be present as a hydrous iron oxide, but it would be of interest to know if the water decreases in amount in the change from Stage 2 to Stage 3. The practice of heating titanium minerals may drive off water and moisture and lends doubt as to whether the X-ray pattern of the heated sample is the same as that of the compound before heating.

My third question is: is it possible to decide if the X-ray patterns of the leucoxene in beach sands represent the bulk of the leucoxene present or a few well-crystallized spots or grains? Lines in the X-ray pattern attributed to sphene in the sample of xanthitane mentioned in this discussion came from about one percent sphene because the chemical analysis of the opposite quadrants of the material used for X-ray patterns contains only 0.18 percent CaO. The lines in the X-ray pattern attributed to sphene in the leucoxene associated with ilmenite from Roseland, Virginia, came from a small amount of sphene because only 0.7 percent CaO is left after combining the amount of CaO required to form apatite with the 12.81 percent P_2O_5 in the chemical analysis of this sample. In the electron micrographs of leucoxene that gave the sharp lines of an anatase X-ray pattern no definite crystalline form of anatase similar to that of the synthetic anatase having an identical X-ray pattern could be seen. These observations provoke the question of how small an amount of a well-crystallized mineral such as rutile, anatase, sphene, or brookite need be present to give sharp lines in its X-ray pattern. Also, can one or two percent of such a well-crystallized mineral be coated and masked so completely that it escapes recognition in electron micrographs? Have other observers had similar experience and can they supply information to answer these questions?

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Aug. 1, 1956

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4. Bailey, S. W., Cameron, E. N., Spedden, H. R., and Weege, Randall J., 1956, The alteration of ilmenite in beach sands: ECON. GEOL., v. 51, p. 263–279.
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6. Coil, Fay, 1933, Chemical composition of leucoxene in the Permian of Oklahoma: Am. Mineralogist, v. 18, p. 62–65.
7. McCartney, G. C., 1932, A Petrographic study of the Chester sandstone of Indiana: Jour. Sed. Petrology, v. 1, p. 82–90.
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9. Tyler, S. A., and Marsden, R. W., 1938, The nature of leucoxene: Jour. of Sed. Petrology, v. 8, p. 55–58.
10. Wentworth, C. K., Wells, R. C., and Allen, V. T., 1940, Ceramic clay in Hawaii: Am. Mineralogist, v. 25, p. 24–27.

REVIEWS

The Evolution of the Igneous Rocks. By N. L. Bowen. Pp. xvii + 334; figs. 82. Dover Publications, New York, 1956. Price, $1.85 (paper), $3.50 (cloth).

"This volume has had a profound influence on the younger generation of geologists because it has emphasized the importance of the point that sound principles of physical chemistry underlie geological processes. It showed how a knowledge of the equlibrium relations in silicate systems, in conjunction with field observations on the rocks and studies of the rock-forming minerals, helped to elucidate the nature and mechanism of the processes involved in rock origins." Thus J. F. Schairer, Bowen's longtime associate in the Geophysical Laboratory, introduces this unaltered and unabridged reprinting of the *sine qua non* in the petrology literature. Within the year during which "The Evolution of the Igneous Rocks" appeared Bowen and Schairer published their first collaboration and, because they have been so closely associated, Schairer is preëminently suited to write this introduction.

Perhaps no other book has had an equally profound impact on the thinking of 20th century geologists as has this one. Unfortunately, however, it has long been out of print and libraries seemed always to have too few copies. Students were continually plagued by this shortage because teachers of petrology (as well as economic geology, mineralogy and geochemistry) required reading of the book in their classes.

Can there be an American geologist who does not know this book? Who will not be immensely pleased by its reappearance in print? The original format and pagination have been preserved but the size is slightly reduced from the first edition. Now all students in "hard-rock" geology can at last own their personal copy of this classic with a great reduction over the original sales price.

Kurt Servos

Les Gisements a Parsonsite de Lachaux. By André Poughon and Marcel Moreau. In Science de la Terre, No. 1–2, Tome III, 1955. Université de Nancy. 11 fig., 2 pl.

In this short work, a description is given of very peculiar uranium ore deposits, found nowhere else in the world, which consist mainly of parsonsite and a few other rare secondary minerals of the uranium family. A brief but careful study of the mines: Etang de Reliez, Gagnol, Bancherelle, and Reliez follows the generalities by which the authors have previously reminded the reader of the mineralogical and chemical characteristics of parsonsite.

Stress is laid on the unusual uranium mineralization, which is made only by secondary minerals, mainly parsonsite, without any pitchblende.

The authors have proposed three hypotheses in order to explain the origin of the ore: emplacement with sulfides, emplacement with the porphyrites, and finally emplacement governed by local tectonics.

For each of the four mines, a critical study of the favorable elements of

mineralization and a metallogenetic interpretation of the ore deposits based on mineralographic observations is made.

This work is illustrated by a few sketches, block diagrams, and photographs.

JEAN BERARD

FORT CHIMO, QUEBEC,
Aug. 13, 1956

Inhaltsverzeichnisse sowjetischer Fachzeitschriften. By Zentralstelle für Wissenschaftliche Literatur, Berlin, Germany. Akademie Verlag, Berlin. D. M. 3.00 monthly.

Considerable geological research is being done in the Soviet Union, the results of which are not normally available in the United States.

About four years ago the Zentralstelle für Wissenschaftliche Literatur in Berlin, Germany, started an abstracting series of Russian scientific publications, including geological and geophysical material, which makes available the results of current Russian research. Problems of geochemistry, in which the Russians have made considerable progress, are also included in this series of abstracts.

The abstracts are published on a monthly basis and follow the original Russian papers within a few months of the publication data. Some are translations of the author's abstracts, others are summaries by the translators. The geological abstracts are included in Series (Reihe) III A, with geophysics, geography, astronomy, physics and mathematics.

Examples of recent abstracts include such diverse subjects as magmatic segregation, anthracite deposits, modern theories on the origin of oil, oxygen of subterranean waters and its geochemical significance, structure and origin of the Dnepr-Donetz basin, and sedimentary cycles in the deposition of the lower Jurassic of Dagestan.

The following journals are among those covered: Bjulletén Moskovskogo obščestva ispytatelej prirody, otdel geologičeskij (Transactions of the Moscow Academy of Science, Section Geology), Izvestija Akamemii Nauk SSSR, Serija geologičeskaja (Bulletin of the Academy of Science of U.S.S.R., Series Geology), Vestnik Leningradskogo universiteta, Serija geologii i geografii (Transactions of Leningrad University, Series Geology and Geography), Doklady Akademii nauk SSR (Bulletin of the Academy of Science USSR), Vestnik Akademii nauk SSR (Transactions of the Academy of Science USSR), Zapiski Vsesojuznogo mineralogičeskogo obščestva (Transactions of the Society of Mineralogists).

GERALD M. FRIEDMAN

STANOLIND OIL AND GAS COMPANY,
TULSA, OKLAHOMA,
Sept. 15, 1956

Introduction to Microfossils. By D. J. JONES. Pp. 380; illus. Harper & Brothers, New York, 1956. Price, $6.50.

This is the first text book on microfossils and it should be welcomed by teacher, student and practicing petroleum geologist. The work is scholarly and the scope is broad. It is beautifully illustrated with about 100 plates showing more than 1,000 fossil forms.

The author starts with a chapter on collection, preparation and preservation of microfossils, giving the simplest and most practical procedures. The following chapter gives a synoptic classification of organisms with reference to microfossils.

Succeeding chapters describe and illustrate microfossils representing all major animal and plant groups, including spores, pollens, fossil seeds and wood fragments, and the application of the data to practical geological problems in economic and exploration geology. The last three chapters cover the environmental significance of microfossils, stratigraphy of fossils, and applied micropaleontology. Five appendices cover the use and care of the microscope, classification and nomenclature of organisms, illustration of microfossils, glossary of generic and specific names in common use, and a very valuable general glossary. There is a general index and an index of fossils.

The author brings to this work a rich experience as Research Geologist and Chief of the Geological Research Section of the Phillips Petroleum Company, before taking up his teaching work at the University of Utah.

The book will find immediate demand by advanced students in micropaleontology and by practicing economic and petroleum geologists.

The Potentials About a Point Electrode and Apparent Resistivity Curves for a Two-, Three- and Four-Layer Earth. By H. M. MOONEY and W. W. WETZEL. Pp. 146 and set of curves. Univ. of Minnesota Press, Minneapolis, 1956. Price for text $4.50, for curves $15.00, complete, $18.00.

This elaborate publication consists of a small text, and a large folder containing 2,300 sheets of curves. The text contains a chapter on the use of tables and curves, a second on the mathematical basis for the tables and curves, and a third one consisting of tables for (a) computing potentials about a point electrode, (b) of remainder terms, and (c) of the potential function. These tables of 117 pages make up most of the text. The chief value of the work is the set of "Master Resistivity Curves for a Two-, Three- and Four-Layer Earth." These 2,300 sheets are printed on logarithmetric coordinate paper 9×13.5 inches in size and are intended for quantitative interpretation of resistivity field data and to provide the interpreter with an understanding of the expected behavior of field curves under a great variety of conditions. The curves provide data for all interpretations of resistivity surveys.

BOOKS RECEIVED

V. RAMA MURTHY

Generalites. 19th Int. Geol. Congress, Vol. 22, Algiers, 1956. Pp. 387. *Lists of members, participant and non-participant, work of the Commission, etc.*

Géologie Appliquée aux Grands Travaux du Maroc. 19th Int. Geol. Congress, Monog. Régionales, Vol. 2. Rabat, Morocco, 1954. Etude de quelques emplacements de barrage. P. LEVEQUE. Pp. 193; pls. 5; figs. 61. *Case histories of four dam-building projects undertaken in French Morocco. New techniques and original methods of applied geology are described.*

Bibliografia Brasileira de Quimica Tecnologica. Instituto Nacional de Tecnologia, Vol. 1, Rio de Janeiro, 1954. Pp. 153.

Calculo de Oleoductos. CARLOS E. PACANDET, Ed., Universidad Nacional de Cuyo, Mendoza-Republica, Argentina, 1953.

Report of Minister of Mines, 1955. W. K. KIERNAN. British Columbia Department of Mines, Victoria, 1956. Pp. 275; pls. 12; figs. 3; tbls. 16. *Total mineral production of British Columbia in 1955 had a value of $174,710,606.*

Trends of production for such metals as copper, zinc, lead are discussed. Statistics of production of natural gas in British Columbia published for the first time in this report. Good index is appended.

La Chronique des Mines d'Outre-Mer. Bureau d'Études Geologiques et Minieres Coloniales, Paris, 1956. Pp. 30.

Bulletin Géodésique, The Journal of the International Association of Geodesy. J. J. LEVALLOIS, Ed., London, 1956. Pp. 61. *Scientific notes and international chronicles.*

Progress Report, 1955. Pp. 78; fig. 1. Geological Survey of Great Britain, London, 1956. Price 4s. 6d. *District reports, sectional reports, and reports of Museum of Practical Geology.*

Mineral Resources Policy—a Symposium. Pp. 146; tbls. 1. Inst. Min. and Metall., London, 1956. Price 10s. 6d. *Collection of papers on mineral policy of Great Britain, mineral development and research in the U.S.A. and Canada. Extensive discussion of the papers contributed is included.*

Boletin del Centro de Documentacion Cientifica y Tecnica de Mexico. Sec. 1. Pp. 807–843. Vol. 5; No. 5, Mexico City. *Reference index to papers on mathematics, astronomy, astrophysics, physics, geology, geophysics and geodesy.*

Geological Survey Department, Nyasaland, Ann. Rep. for 1955. Pp. 24. Zomba, Nyasaland, 1956. Price 2s. 6d.

Ontario Department of Mines. Mining Operations in 1954. Annual Report, Vol. 64; Part 2, 1955. Pp. 154. Toronto, 1956. *Mine to mine statistics of the mines in production in 1954, listed alphabetically according to the mineral or metal.*

Acta Geologica Taiwanica, Science Reports of the National Taiwan University, No. 7, 1955. Pp. 65. Taipei, Taiwan, China. *Four geological articles.*

Geology of Part of South-East Uganda, with Special Reference to the Alkaline Complexes. Geol. Surv. Uganda, Memoir No. 8. Pp. 75. Entebbe, Uganda, 1956. Price shs. 20. *Alkaline complexes contain phosphate, vermiculite, iron ores and pyrochlore.*

Atomic Energy Commission, 20th Semiannual Report. Pp. 255. U.S. Atomic Energy Comm., Washington, 1956. *Record of progress in all aspects of United States atomic energy program, under a collaborated effort of Government and private industry. Increase in the output of total raw material supply. Several programs of research into peaceful uses of atomic energy, training of personnel and international agreements discussed.*

Symposium on Rock Mechanics. Quart. Colo. School of Mines, Vol. 51, No. 3. Pp. 231, Golden, Colo., 1956. Price $2.00. *Several excellent papers on rock mechanics. Divided into five parts: rock failure; design and support of underground openings; mining by block caving; rock fragmentation by blasting; and general discussion. All the papers are well illustrated with diagrams and sketches.*

Economic and Engineering Aspects of Mica and Associated Minerals, New Mexico (a Professional Report to the Commission). S. H. GLASSMIRE, JR. and J. P. WAHLEN. Pp. 26; figs. 3. New Mex. Econ. Devel. Comm., Sante Fe, New Mexico, 1956.

Nuclear Energy and the Fossil Fuels. KING HUBBERT. Pp. 40; figs. 30; tbls. 6. Pub. No. 95, Shell Develop. Co., Houston, Texas, 1956. *Mathematical and statistical analysis of production rates of fossil fuels, as compared to the total reserves, poses a great problem. Nuclear fuels hold a good promise for the "foreseeable future."*

Geologia de la Terraza Continental. T. G. CASTELLANOS. Pp. 65. Cordoba Univ., Argentina, 1955. *Discussion of continental shelf as an international boundary.*

Geology of the Huntington Lake Area Calif. Pp. 25; pl. 1; figs. 16. Calif. Dept. Nat. Res., Special Rep. 46, 1956. Price 75¢.

Carte Géologique du Congo Belge et du Ruanda-Urundi, Légende Générale. Pp. 12. Liege, 1955. Fourth edition. *Additions and modifications.*

Meteorites and Related Bodies, with a Guide to the Collection of the Geological Museum, Cairo. A. A. ATTIA, E. M. EL-SHAZLY, M. O. MOHARRAM and A. A. HUZAIN. Pp. 53; figs. 10. Egypt, Mineral Res. Dept. Geol. Museum Pap. No. 1, Cairo, 1955. Price P.T. 15.

Geological Survey of Egypt.

A Preliminary Report on El 'Atawi Copper Deposit, Eastern Desert. E. M. EL SHAZLY and A. H. SABET. Pap. No. 2. Cairo, 1955. Pp. 6; pls. 5. Price, P.T. 10.

Geology of Gebel Mudargag West Area Nugrus Sheet—Eastern Desert. E. M. EL SHAZLY and M. M. HAMADA. Pp. 26; pls. 18. Cairo, 1954. Price, P.T. 60.

Geology of Umm Lassaf District. M. S. AMIN and I. H. MOHAMED. Pp. 16; pls. 12. Cairo, 1955. Price, P.T. 45.

Geology and Mineral Deposits of Umm Rus Sheet. M. S. AMIN. Pp. 51; pls. 34. Cairo, 1955. Price, P.T. 90.

Illinois Geological Survey—Urbana, 1956.

Bull. 79. Oil and Gas Development in Illinois in 1954. A. H. BELL and VIRGINIA KLINE. Pp. 59; figs. 23; tbls. 13. *Details of production and development are discussed by countries.*

Circ. 208. Mineral Production in Illinois in 1955. W. H. VOSKUIL and W. L. BUSCH. Pp. 40; figs. 5; tbls. 15. *Brief economic analyses of the mineral industries with maps and tables showing production statistics.*

Circ. 219. Coking Coals of Illinois, Their Use in Blends for Metallurgical Coke. H. W. JACKMAN, R. L. EISSLER and F. H. REED. Pp. 30; tbls. 16; appendix. *Low expansion Illinois coals can be blended with high expansion eastern coals.*

Indiana Geological Survey—Bloomington, 1956.

Bull. No. 9. High-Silica Sand Potentialities of the Ohio River Formation. A. P. PINSAK. Pp. 54; figs. 7; tbls. 7. *Sand from the Ohio River formation can be treated so as to meet specifications for glass-sand.*

Progress Rept. No. 7. Thickness of Drift and Bedrock Physiography of Indiana North of the Wisconsin Glacial Boundary. W. J. WAYNE. Pp. 65; pl. 1; figs. 10. *Thickness of glacial drift in Indiana is determined largely by preglacial topography developed on Paleozoic rocks.*

Geological Survey of Kansas—Lawrence, 1956.

Bull. 120. Geology and Ground-Water Resources of Reno County, Kansas. C. K. BAYNE. Pp. 129; pls. 3; figs. 23; tbls. 11. *Unconsolidated sands and gravels of Pleistocene age form the most important aquifer in the area.*

Belo Horizonte, Brazil, 1956.

Publ. No. 5. Notas Sobre a Geologia e Petrografia do Planalto de Pocos de Caldas Mg. J. J. R. Branco. Instituto de Pesquisas Radioativas. Pp. 72.

Publ. No. 6. Conglomerado do Samburá. J. J. R. Branco. Instituto de Pesquisas Radioativas. Pp. 9; figs. 3. *Geologic map of structure sections.*

North Dakota Geological Survey—Grand Forks, 1956.

Bull. 31. Geology of North Dakota. J. L. Hainer. Pp. 44; pls. 3; figs. 27. *Concise account of geology of North Dakota for students and laymen; with geologic, topographic and physiographic maps.*

Bull. 30. Guide for Geologic Field Trip in Northeastern North Dakota. W. M. Laird. Pp. 20; figs. 6; tbls. 1.

Repts. of Investigation Nos. 24, 25 and 26. Geology of the Lower Pipestem Creek Area North Dakota. R. J. Kresl. *Three maps with descriptions.*

Production Statistics and Engineering Data Oil in North Dakota. W. M. Laird. *Production statistics and engineering data on the oil and gas pools for the first half of 1956.*

Northern Rhodesia, Lusaka, 1956.

Annual Report for the Year 1955, Department of Geological Survey. W. H. Reeve. Pp. 10. Price 2s. *Major item in the work of the department was the continued exploration of the Kandabwe coal area.*

Annual Report for the Year 1955, Department of Water Development and Irrigation. T. W. Longridge. Pp. 11. Price 1s.

Bureau of Mines, Special Projects Series—Manila, 1955–56.

Pub. No. 1. Geology and Coal Resources of the Bulalacao Region Mindoro Oriental. J. M. Weller and J. F. Vergara. Pp. 37; pls. 3; figs. 5. *In spite of the appreciable reserves of coal, the possibility of developing large mines is not good due to many inherent difficulties.*

Pub. No. 2. Geology and Coal Resources of the Pañganiban Region, Catanduanes. Oscar Crispin, J. M. Weller and Cesar Ibañez. Pp. 23; pls. 3; figs. 5. *Estimated reserves of a million tons of medium volatile, high-ash coal.*

Pub. No. 3. Geology and Coal Resources of Batan Island, Albay. Oscar Crispin, J. M. Weller and Jose F. Vergara. Pp. 51; pls. 5; figs. 3; tbls. 4. *One of the more favorable localities for large scale mining of coal in Philippines. Reserves up to a depth of 100 m. below sea level are estimated to be 11½ million tons.*

Pub. No. 4. Geology and Coal Resources of the Hitoma-Manambrag Region, Catanduanes. V. de los Santos and J. M. Weller. Pp. 26; pls. 2; figs. 2; tbls. 3. *Reserves of one million tons of coal, but no transportation facilities.*

Pub. No. 5. Geology and Coal Resources of the Gatbo Peninsula, Bacon-Prieto Diaz-Gubat Region, Sorsogon. C. B. Ibañez, Harley Barnes, and J. de la Cruz. Pp. 16; pls. 2; figs. 1. *Not a favorable area for large scale coal mines development.*

Pub. No. 6. Geology and Coal Resources of Semirara Island, Antique. J. F. Vergara. Pp. 22; pls. 2; figs. 3; tbls. 2. *Available coal is of little economic value due to its high moisture and low calorific value.*

Pub. No. 9. Geology of the Copper Deposits of the Hixbar Gold Mines, Inc., Rapu Rapu Island, Albay. A. R. KINKEL, JR., and S. SAMANIEGO. Pp. 23; pls. 4. *About 230,000 metric tons of high-grade copper ores.*

Pub. No. 10. Geology of the Botolan Copper Mine, Botolan, Zambales. A. R. KINKEL, JR., and S. SAMANIEGO. Pp. 11; pls. 4. *Chalcopyrite and pyrrhotite with quartz in faults and shear zones in a gabbro.*

Tanganyika, Geological Survey, Dodoma, 1955–56.

Geol. Map sheets: Madaba, Uluguru and Mpwapwa. Scale 1:125,000. *Brief explanations of geology.*

Virginia Division of Geology—Charlottesville, 1956.

Rept. No. 19. The Mineral Industry of Virginia (1953). N. B. MELCHER and ALVIN KAUFMAN. Pp. 14; tbls. 7. *Mineral production statistics for 1953, and a county-wise survey of the situation.*

Bull. 70. Sulfide Mineralization in the Shenandoah Valley of Virginia. PAUL HERBERT, JR., and R. S. YOUNG. Pp. 53; pls. 15; figs. 10; tbls. 3. *Low temperature hydrothermal sphalerite in large-scale shatter breccias.*

U. S. Geological Survey—Washington, D. C., 1956.

Bull. 1016. The Wishbone Hill Districts, Matanuska Coal Field, Alaska. F. F. BARNES and T. G. PAYNE. Pp. 87; pls. 20; figs. 1; tbls. 4. Price, $2.50. *Bituminous coal occurs in the upper part of Chickaloon formation. Indicated reserves 50 million tons; inferred reserves, 52 million tons.*

Bull. 1024-E. Pyrite Deposits at Horseshoe Bay Latouche Island Alaska. F. A. STEJER. Pp. 107–122; pls. 12; figs. 11–14. Price 45 cts. *Pyrite deposits at Horseshoe Bay, Alaska, might be a possible source of sulfur.*

Bull. 1027-J. Geology of the Stanford-Hobson Area Central Montana. J. D. VINE. Pp. 405–469; pls. 45–47; figs. 52–61; tbls. 1–6. Price, $1.25. *Coal, gypsum, and oil potentialities exist in the Stanford-Hobson area, Central Montana.*

Bull. 1027-M. Reconnaissance Geology of Western Mineral County Montana. R. E. WALLACE and J. W. HOSTERMAN. Pp. 575–611; pls. 48–51; figs 73–75. Price, $1.25. *Replacement and fissure-filling veins of galena, sphalerite, tetrahedrite and chalcopyrite are found in Western Mineral County, Montana.*

Bull. 1030-C. Uranium Deposits at Base of the Shinarump Conglomerate Monument Valley Arizona. I. J. WITKIND. Pp. 99–130; pls. 5–6; figs. 12–27. Price, 65 cts. *Uranium occurs in conglomeratic sandstone in the Shinarump conglomerate in the Monument Valley, Arizona.*

Bull. 1030-E. Study of Radioactivity in Modern Stream Gravels as a Method of Prospecting. R. T. CHEW, III. Pp. 149–169; pls. 8; figs. 33–41. Price, 25 cts. *Radioactive determination of gravels downstream from uranium deposits might be a useful prospecting tool under certain conditions.*

Bull. 1036-G. X-ray Powder Data for Uranium and Thorium Minerals. CLIFFORD FRONDEL, DAPHNE RISKA and J. W. FRONDEL. Pp. 91–152. Price, 25 cts. *X-ray powder data for 67 uranium and thorium minerals.*

Bull. 1037-A. General Geology and Phosphate Deposits of Concepción del Oro District, Zacatecas Mexico. C. L. ROGERS, ZOLTAN DE CSERNA, EUGENIO TAVERA, and SALVADOR ULLOA. Pp. 99; pls. 2; figs. 27; tbls. 8. *Marine phosphorites occur in one unit of the La Caja formation. Reserves calculated in the Sierra de Santa Rosa amount to some 5,000,000 metric tons averaging 21.1 percent* P_2O_5.

Bull. 1042-A. Geology of the Johnson Creek Quadrangle, Caribou County, Idaho. R. A. GULBRANDSEN, K. P. MCLAUGHLIN, F. S. HONKALA, and S. E. CLAGAUGH. Pp. 23; pls. 2; figs. 1. Price, 75 cts. *Geological map of the Johnson Creek 7½-minute quadrangle with special bearing on structural features.*

Bull. 1042-B. Airborne and Ground Reconnaissance of Part of the Syenite Complex Near Wausau, Wisconsin. R. C. VICKERS. Pp. 25–44; figs. 2–6. Price, 15 cts. *Discovery of 12 radioactive mineral localities near Wausau, Marathon County, Wisconsin.*

Prof. Paper 284. Geology and Ore Deposits of the Zimapán Mining District, State of Hidalgo Mexico. F. S. SIMONS and EDUARDO MAPES V. Pp. 127; pls. 14; figs. 69. *Detailed geology of silver-lead-zinc mining area in south, east-central Mexico. Deposits are of mesothermal replacement type, late Miocene (?) or early Pliocene (?) in age.*

Prof. Paper 288. Surficial Geology and Geomorphology of Potter County Pennsylvania. C. S. DENNY. Pp. 69; pls. 8; figs. 30; tbls. 3. *A restored contour map of summits of Appalachian Plateau in north-central Pennsylvania gives a surface corresponding roughly to the structure and there is no direct evidence to believe that it was ever a peneplain. No new data on the origin of the cross-axial drainage is provided by the geomorphic analysis.*

Water-Supply Paper 1317. Compilation of Records of Surface Waters of the United States through September 1950.—Part 13. Snake River Basin. J. V. B. WELLS. Pp. 557; pls. 1; figs. 2.

Water-Supply Paper 1328. Ground-Water Resources of the Hopkinsville Quadrangle, Kentucky. E. H. WALKER. Pp. 97; pls. 4; figs. 20; tbls. 7. Price, 70 cts.

Water-Supply Paper 1356. Geology and Ground-Water Resources of the Henderson Area Kentucky. E. J. HARVEY. Pp. 225; pls. 13; figs. 16; tbls. 13.

Water-Supply Paper 1363. Hydrology of Indiana Lakes. J. I. PERREY and D. M. CORBETT. Pp. 345; figs. 139; tbls. 1. Price, $1.25.

SCIENTIFIC NOTES AND NEWS

J. D. HESS has opened offices in El Centro, Calif., as a consulting ground-water geologist. In addition to general ground-water problems, Mr. Hess will serve the fields of geo-chemical interpretation of waters and drainage.

A. M. SHORT is head of the geological section, Directorate of Petroleum and Mineral Affairs, Ministry of Finance, Jeddah, Saudi Arabia.

A. C. THOMPSON is geologist with Union Carbide Nuclear Co. at Bishop, Calif.

P. I. EIMON has returned to the staff of the American Smelting & Refining Co., with headquarters at the company's Eastern U. S. Div., Knoxville, Tenn. Mr. Eimon was formerly associated with the Dept. of Geology, University of California, at Berkeley.

V. D. PERRY, chief geologist, the Anaconda Co., is moving the headquarters of the geological department from Salt Lake City to 25 Broadway, N.Y.C.

G. C. ANSTUTZ, formerly with Cerro de Pasco Corp., Peru, has been elected Associate Professor of Geology, Missouri School of Mines and Metallurgy.

F. M. CHACE is the new assistant director of exploration for the M. A. Hanna Co. He will work with J. K. Gustafson, director of exploration, in Cleveland, Ohio.

A. J. THULI has been appointed assistant chief engineer of the Utah Copper Division, Kennecott Copper Corp.

D. D. BAKER is the new director of the mining division in Grand Junction, Colorado, for the U. S. Atomic Energy Commission.

J. D. PRENDERGAST has joined the staff of Sulmac Explorations, Ltd., as chief geophysicist. For the past three years he has been a senior geophysicist on the staff of the International Nickel Company of Canada, Ltd.

G. K. ALLEN has been elected President of the Institution of Mining and Metallurgy (London) for 1957–58.

GABOR DESSAU has returned from the Geological Congress in Mexico to his assignment as UNESCO expert with the Israel Institute of Technology in Haifa. His task is the establishment of a mining engineering department. He will stay in Haifa for another year, and then return to his academic and consulting activities in Italy.

S. F. TURNER and R. L. WELLS have formed an association known as Turner and Associates, Consulting Geologists, in water, mining and geophysics; 350 East Camelback Road, Phoenix, Arizona.

W. J. SHEDWICK, JR., consulting mining engineer, Paseo de la Reforma 20–302, Mexico, D. F., in late October terminated a sixteen months study and exploration by means of diamond drilling extensive commercial gypsum deposits in the states of San Luis Potosi, Puebla and Colima, Republic of Mexico.

The U. S. Geological Survey has reorganized its Water Resources Division to integrate the program planning and the operations of the division, to decentralize its administration and to improve facilities for hydrologic studies. This in turn will permit a more effective utilization of the Survey's staff in basic research on the occurrence and behavior of water and in the interpretation of basic water data.

The revised plan provides an assistant chief of division for operations, R. L. NACE; an assistant chief of division for program and development, DR. L. B. LEOPOLD; an administrative officer in the immediate office of the division chief, FRANK BARRICK, JR. In addition, two field representatives of the division chief to be known as division hydrologists have been named: A. M. PIPER for the Pacific Coast area with headquarters in Menlo Park, Calif.; and G. E. FERGUSON for the Atlantic Coast area with his office in Arlington, Va. Two other division hydrologists for the Rocky Mountain, and Mid-Continent areas will be named later. Within the division a new branch has been added, that of General Hydrology, headed by C. C. MCDONALD, chief. Thus there are now four branches: Ground Water, Surface Water, Quality of Water, and General Hydrology. Other changes in branch structure are contemplated in accord with recommendations, and will be announced later.

Behre Dolbear & Company, Inc., announce that F. H. MADISON, Mining Engineer, has become an associate member of their firm. Mr. Madison retired from Government service on November 1st after many years service as Chief of the Mining Section (Natural Resources) of the Internal Revenue Service and Principal Engineer (Mining) of the U. S. Treasury Department.

G. C. DILLMAN, who retired October 1st as president of Michigan College of Mining & Technology, has been succeeded by J. R. VAN PELT, president of the Montana School of Mines since 1951.

B. W. KERRIGAN has been appointed secretary of the Institution of Mining and Metallurgy, London.

R. W. PHENDLER, JR., has been appointed resident geologist at the Cerro de Pasco Corporation's San Cristobal mine at Mahr Tunnel, Peru, South America. Formerly he was with National Explorations, Ltd., Uranium City, Sask.

L. B. MOON was general chairman of the Northwest Mining Association's 62nd annual convention in Spokane, Washington, November 30–December 1. Mr. Moon is district geologist in charge of the Spokane Northwest district office of Bear Creek Mining Co.

V. D. PERRY, chief geologist for the Anaconda Company, recently moved his headquarters from Salt Lake City to New York.

R. B. MULCHAY of Tucson, Arizona, will be in charge of Anaconda explorations in western United States and Mexico as assistant chief geologist. In addition he will supervise geological work at Mexico operations and in all western states with the exception of Montana.

L. G. NONINI, former Wallace, Idaho geologist, was honored recently by the Korean government for his outstanding service in his capacity as chief of the mining section of the United Nations Korean Reconstruction Agency.

R. L. LOOFBOUROW, consulting mining engineer and geologist, returned recently to his headquarters in Minneapolis, Minnesota, following a trip around the world.

F. G. SHARP, until recently superintendent of the Hyderabad Gold Mines Company Ltd., and representative in Hyderabad for John Taylor & Sons, has accepted the position of superintendent of Mysore Gold Mining Company (KGF) Ltd., Mysore State, South India.

E. T. KNIGHT has been appointed general manager of the New York and Honduras Rosario Mining Company, with headquarters in Honduras.

The United States Atomic Energy Commission conducted an 18-day tour of uranium deposits and ore processing facilities in the western United States for 36 distinguished foreign geologists and engineers as part of a program for inter-

national cooperation in uranium exploration. The group began the tour September 27 at Albuquerque, New Mexico.

C. R. JOKISCH, formerly mining engineer, Britannia Corp., Britannia Beach, B. C., Canada, is now at Snow Lake, Manitoba.

B. E. THOMAS has joined the Geology Department, San Diego State College, California. Formerly he was doing consulting work in Albuquerque, New Mexico.

A. O. HALL has left Northwestern Dept., American Smelting & Refining Co., where he was chief geologist, to become exploration engineer for Climax Molybdenum Co., Vancouver, B. C.

J. D. MORGAN, JR., has opened a consulting office in Washington, D. C. Prior to this, Dr. Morgan had been with the Defense Production Administration in Korea, and the Office of Defense Mobilization in Washington.

THAYER LINDSLEY, founder of Falconbridge Nickel Mines 28 years ago, has retired as president and will devote his time to a newly formed exploration company.

PAUL KENTS is resident geologist for New Consolidated Canadian Exploration Ltd., Quebec. Formerly he was senior exploration geologist of Northern Peru Mining Corp.

A. E. Moss, chief engineer-geologist of the Iron Ore Co. of Canada, has left Montreal for the company's offices in Schefferville, Quebec.

KANJI SHIOBARA, geologist for Mitsui Mining & Smelting Co. Ltd., has been transferred from the Tokyo office of the company to their Kamioka Mine, Gifu-ken, Japan.

C. T. SISON, previously employed as geologist with the Elizalde & Co. Inc., Manila, P. I., has formed the Republic Resources & Development Corp., of which he is general manager, in Manila.

G. S. HUMEHAS resigned from the Canadian Department of Mines and Technical Surveys to become geologist at Westcoast Transmission Co. Ltd., Calgary, Alberta.

W. R. BARTON, JR., U. S. Geological Survey, is now at the Agricultural Research Center, Beltsville, Maryland.

THE INDEX TO THIS VOLUME HAS BEEN REMOVED FROM THIS POSITION AND PLACED AT THE BEGINNING OF THE FILM FOR THE CONVENIENCE OF READERS

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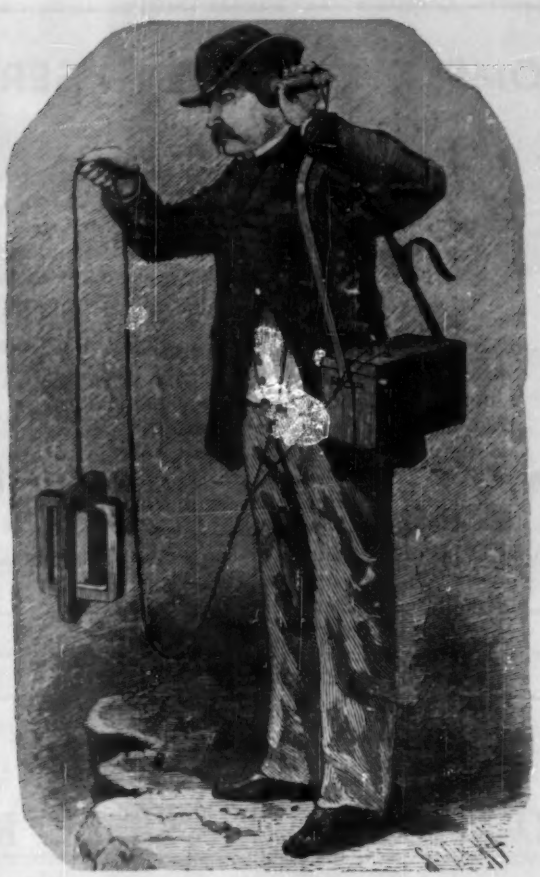

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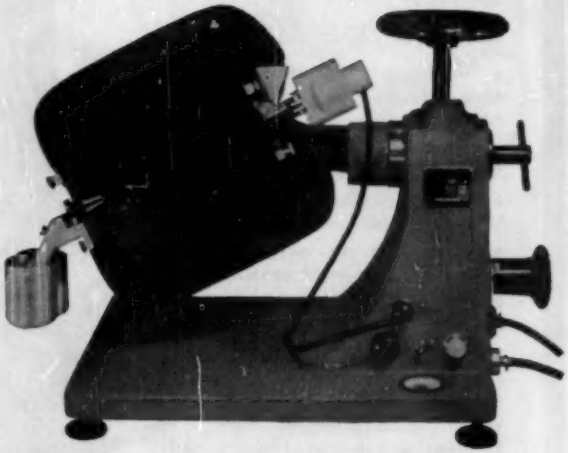

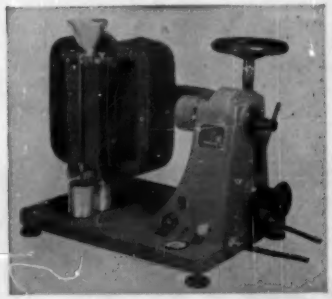

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